

# Overview of energy storage systems in distribution networks: Placement, sizing, operation, and power quality

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## ABSTRACT

The deployment of energy storage systems (ESSs) is a significant avenue for maximising the energy efficiency of a distribution network, and overall network performance can be enhanced by their optimal placement, sizing, and operation. An optimally sized and placed ESS can facilitate peak energy demand fulfilment, enhance the benefits from the integration of renewables and distributed energy sources, aid power quality management, and reduce distribution network expansion costs. This paper provides an overview of optimal ESS placement, sizing, and operation. It considers a range of grid scenarios, targeted performance objectives, applied strategies, ESS types, and advantages and limitations of the proposed systems and approaches. While batteries are widely used as ESSs in various applications, the detailed comparative analysis of ESS technical characteristics suggests that flywheel energy storage (FES) also warrants consideration in some distribution network scenarios. This research provides recommendations for related requirements or procedures, appropriate ESS selection, smart ESS charging and discharging, ESS sizing, placement and operation, and power quality issues. Furthermore, this study identifies future research opportunities in relation to challenges for optimal ESS placement planning, development and implementation issues, optimisation techniques, social impacts, and energy security.

## 1. Introduction

Present distribution networks face a critical period of change driven by various interrelated factors; for example, greenhouse gas (GHG) reduction targets, demand management, power congestion, power quality requirements, integration of renewables, and network expansion and reliability [1–11]. The U.S. Electric Power Research Institute (EPRI) estimated the annual cost of outages to be \$100 billion USD, due to disruptions occurring in the distribution system [12]. Energy storage systems (ESSs) are increasingly being embedded in distribution networks to offer technical, economic, and environmental advantages. These advantages include power quality improvement, mitigation of voltage deviation, frequency regulation, load shifting, load levelling and peak shaving, facilitation of renewable energy source (RES) integration, network expansion and overall cost reduction, operating reserves, and GHG reduction [13–16,6,17–20]. As reported in [21–23], ESSs are expected to effectively relieve the problems posed by power oscillations, abrupt load changes, and interruptions of transmission or distribution systems.

Governmental efforts to reduce emissions have forced the power

sector to reduce its reliance on conventional fossil fuel-based power generation in favour of renewable energy [24–30], largely in the form of wind and solar [31,32]. Even though power generation from renewable energy is more environmentally sustainable, a high reliance on renewable energy can make power distribution systems less reliable [33,19]. ESSs can support renewable energy by providing voltage support, smoothing their output fluctuations, balancing the power flow in the network, matching supply and demand [34–39,18,40–43,21,44–46], and helping distribution companies (network operators and energy retailers) to meet demand reliably and sustainably. These operational challenges can be mitigated by the appropriate utilisation of grid-integrated ESSs [39,23,46,25,26,47–49]. Therefore, there is a great potential for using ESSs, from the viewpoint of both utilities and customers.

Unfortunately, misusing or mislocating ESSs in distribution networks can degrade power quality and reduce reliability as well as load control while also affecting voltage and frequency regulation. Research on ESS technologies, development, applications, and benefits is reported in [41,50,51,17–19,52,34,37,40,53,44,54–62,25,26,47,48,46]. In [34,44,54], several ESS options and their prospects for RES

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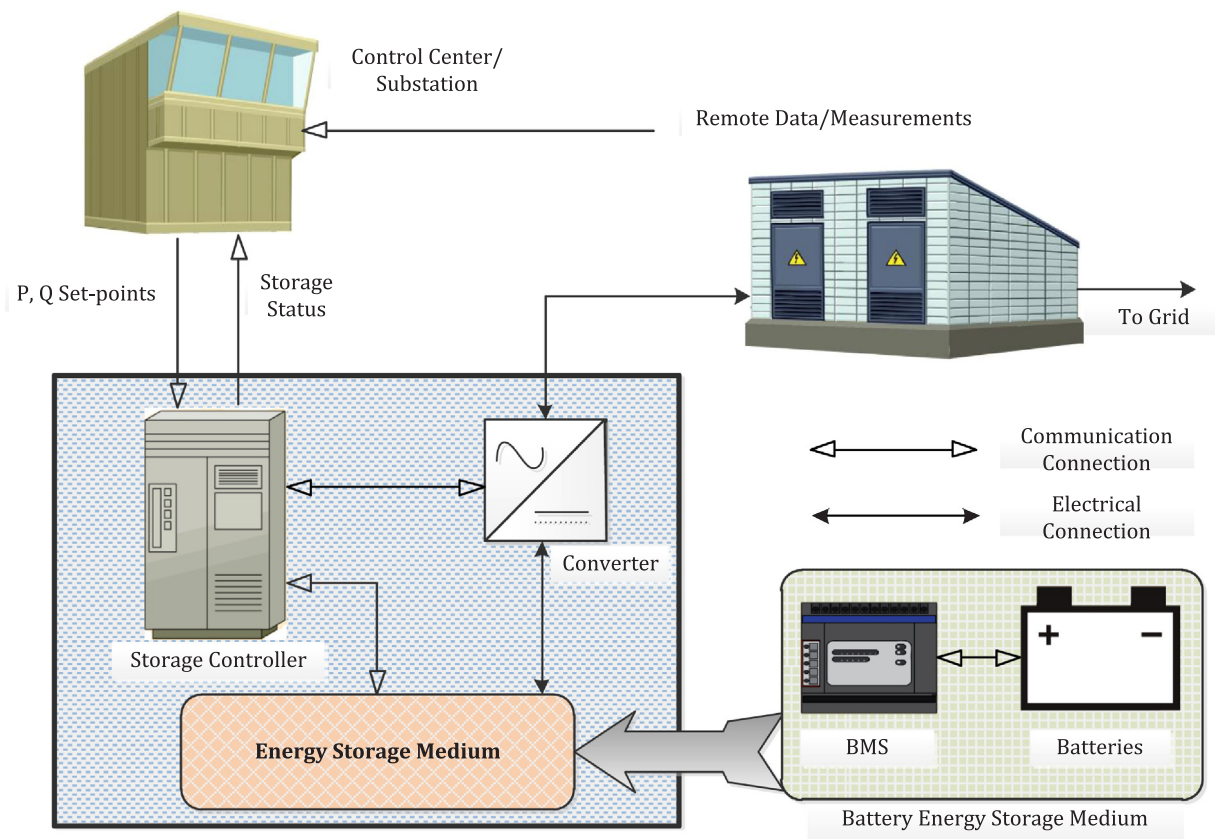


Fig. 1. Conceptual diagram of an ESS.

integration and intermittency are discussed. In [41,37], applications of ESSs for wind energy are studied, while the importance of ESSs for large-scale integration of photovoltaics (PVs) is the focus of [18]. In [25], an ESS, namely, pumped hydro storage (PHS) is used to stable the wind power generation while optimising the generation mix, total CO<sub>2</sub> emissions, and total system costs. [26] investigates the utility-scale application impact of an ESS, e.g., compressed air energy storage (CAES) in a power system scenario considering large RES integration. In [47,48], short term applications of utility-scale ESSs are presented for mitigating negative operational impacts of a high wind-penetrated power system.

An overview of current and future ESS technologies is presented in [53,57,59], while [51] reviews a technological update of ESSs regarding their development, operation, and methods of application. [50] discusses the role of ESSs for various power system operations, e.g., RES-penetrated network operation, load leveling and peak shaving, frequency regulation and damping, low voltage ride-through ability, and power quality improvement. [17] discusses ESS options for some high-power applications, e.g., frequency regulation, voltage control, oscillation damping, and voltage ride-through. [46] presents an economic and technical overview of the role and significance of ESSs and smart grid technologies for future renewable power systems. The policy recommendations and benefits of using ESSs in smart grid are presented in [19] and [52], respectively. Likewise, [58] reviews the various ESSs in terms of innovative technologies, energy policies, and regulatory regimes. The potential of ESSs for various services in distribution networks is reviewed in [55,56], while their operations are discussed in [60]. In [61], research on ESS allocation is reviewed to provide insights into ESS integration issues and challenges in distribution networks along with guidelines for future ESS-related research. In [62], optimal ESS planning is discussed, including optimal ESS locations, energy capacity, and power rating determination in distribution networks.

Although various investigations on ESS options and application benefits are carried out in the literature discussed above, very few

studies [61,62] focus on a review of ESS placement, sizing, and operation. However, more emphasis is required on optimal ESS placement, including sizing and operation as well as power quality, and this paper addresses that need. The main contributions of this paper are summarised as follows:

- The paper provides a comprehensive review of ESSs from a distribution network perspective, including ESS benchmarks, ESS technologies and selection, and ESS charging-discharging rules.
- Optimal ESS sizing, placement, and operation are reviewed thoroughly (based on the recent literature) and critically analysed by highlighting the strategies that are used, advantages, and the scope of future research. The paper also discusses tools and their suitability for system modelling, simulation, and analysis, considering ESS applications in distribution networks.
- The paper discusses various issues related to the power quality of distribution networks and their mitigation scopes with ESSs.
- The research verifies the importance of hybrid meta-heuristic optimisation approaches for obtaining optimal solutions, rather than other optimisation techniques.
- The paper identifies the challenges for ESS development and placement and discusses the ESS contributions to energy security and society.
- The research presents several key findings which will benefit researchers by highlighting potentially important directions for future research. The content of this paper is organised as follows: Section 2 describes an overview of ESSs, effective ESS strategies, appropriate ESS selection, and smart charging-discharging of ESSs from a distribution network viewpoint. In Section 3, the related literature on optimal ESS placement, sizing, and operation is reviewed from the viewpoints of distribution network operation and power quality issues. Section 4 discusses the challenges and distribution network performance factors that should maximise the economic and social impact benefits. Finally, Section 5 concludes the paper by highlighting future research recommendations.

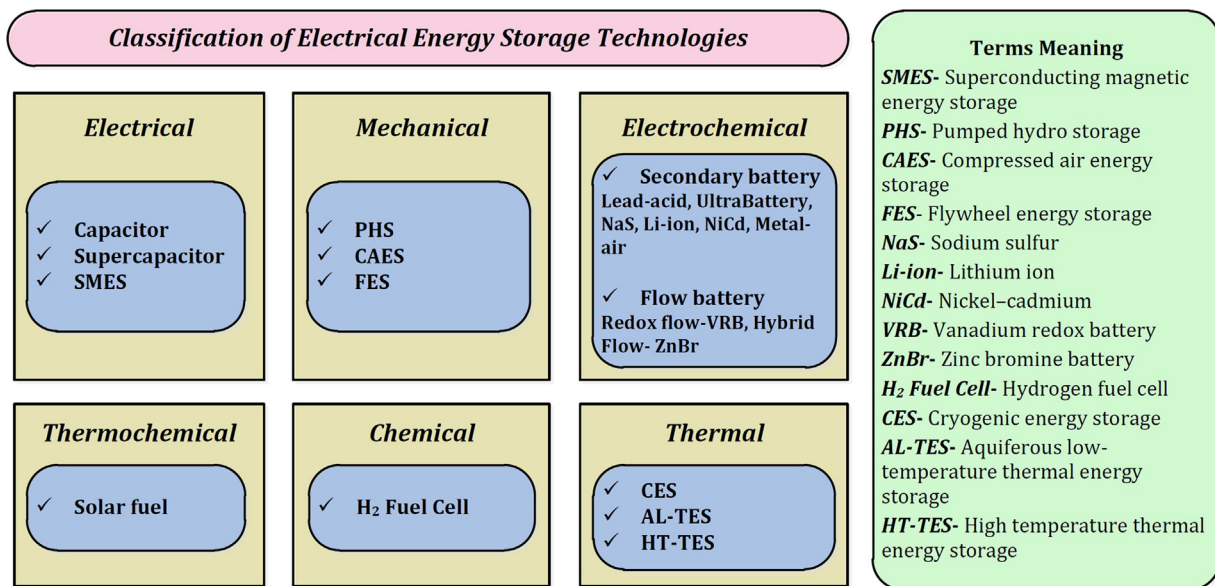


Fig. 2. Different types of ESS technologies for distribution networks.

## 2. Energy storage systems for distribution networks

### 2.1. Energy storage systems

For distribution networks, an ESS converts electrical energy from a power network, via an external interface, into a form that can be stored and converted back to electrical energy when needed [16,63,64]. The electrical interface is provided by a power conversion system and is a crucial element of ESSs in distribution networks [65,66]. Fig. 1 [67] is a conceptual diagram of a grid-connected ESS, including internal and external configurations.

ESSs are usually equipped with essential management and control components that underpin safe and reliable operation of storage facilities. The objective is not only to facilitate local management but also to have coordinated control over other components during grid-scale applications. The power electronics components of the grid-connected ESSs modulate the waveforms of voltage and current as needed to or from the grid. A storage controller and converter manage ESS operations, define the active and reactive power set-points (P and Q) for the ESS and provide intelligent decision-making. Depending on the design, the P and Q set-points for a certain ESS application can be controlled locally or remotely. The “Energy Storage Medium” corresponds to any energy storage technology, including the energy conversion subsystem. For instance, a Battery Energy Storage Medium, as illustrated in Fig. 1, consists of batteries and a battery management system (BMS) which monitors and controls the charging and discharging processes of battery cells or modules. Thus, the ESS can be safeguarded and safe operation ensured over its lifetime. However, large-scale ESSs require a BMS hierarchy which involves a master control module to coordinate the charging and discharging of the slave control modules.

### 2.2. Effective storage strategem

The ESS can store energy to produce electricity and discharge it, depending on the demand or cost benefits [6,16]. Benchmarks for an effective ESS include [68]:

(i) Dispatchability – responsiveness to electricity demand fluctuations that may occur on various cycles (daily, weekly, and seasonal) due to variations in domestic and industrial loads and changes in some environmental factors, e.g., weather conditions.

(ii) Interruptibility – reactivity to the intermittency of renewable energy supplies such as wind and solar, the seasonally alternating

behaviours of hydropower and biomass, and the recurring instabilities associated with fossil-fuel supplies.

(iii) Efficiency – the capacity to recover and reuse energy that is otherwise wasted.

### 2.3. Selection of an ESS for distribution networks

The history of ESSs began in the early 20th century with the use of Lead-acid battery as an ESS to provide power for residual loads on a DC electricity network [44,64,69]. Since then ESS technologies have continued to develop and they are increasingly being used for power system applications such as grid stabilisation, load shifting, grid operational support, power quality improvement, and reliability management [44,34]. Additionally, the increasing grid integration of intermittent renewable distributed generation (DG) significantly change the scenario of distribution network operations. These operational challenges are mitigated by ESS incorporation, which plays a vital role in improving the overall network's stability and reliability [70,44]. The ESSs could also perform an important role in deregulated markets, e.g., providing arbitrage and increasing the value of RESs [70].

With the focus shifting to making these functions a reality, governments worldwide (e.g., EU, U.S., and Japan) encourage the development and deployment of ESSs through nationally supported programmes [44,69]. Consequently, ESSs are frequently used in large-scale applications such as power generation, distribution and transmission networks, distributed energy resources, renewable energy, and local industrial and commercial facilities [69]. The application of ESSs to distribution networks can benefit the supply company, the customer, and the distribution network operator (DNO) as well as the transmission system operator (TSO) and the generation operator (conventional and DG) in numerous ways [52]. In [55], ESS opportunities for stakeholders in the electricity value chain are analysed from the viewpoints of the French distribution system and island networks. The Sandia National Laboratory reports on ESS application benefits in the U.S. by evaluating the cost-benefit of distribution and transmission network upgrade deferral arbitrage and generation capacity credit, and power quality issues [71–73]. An electricity grid can use numerous energy storage technologies as shown in Fig. 2, which are generally categorised in six groups: electrical, mechanical, electrochemical, thermochemical, chemical, and thermal. Depending on the energy storage and delivery characteristics, an ESS can serve many roles in an electricity market [65].

As placement of large-scale ESSs involves substantial investment,



selecting ESSs appropriately on the basis of performance expectations is challenging. The current level of adoption and the technical specifications of different ESS technologies are assessed from technical viewpoints in [69,74,57–59,56]. The ESS inclusion options for increasing RES penetration at a utility level are explored in [34] by comparing their technical characteristics, cost, and environmental impact. Importantly, in [57,15,74,70,45], different ESS technologies are considered based on current state of development, available methods, technology updates, and application potential. Most specifically, in [57,70], different ESS technologies are compared by reviewing various studies which highlight their applications rather than specifying their advantages and disadvantages. Technical comparisons of different ESSs, including their advantages and disadvantages, are provided in [15], although other factors such as capacity, lifetime, charge and discharge times, environmental impact, and various aspects of their application are not considered. More comprehensive comparisons of various ESS technologies for distribution networks are provided in Table 1 [69,74,57,70,34,15,75–77,14,16] and Table 2 [15,74,57,70,75,76].

Table 1 classifies various ESS technologies as electrical, mechanical, electrochemical, thermochemical, chemical, and thermal. These technologies are considered in regard to ESS capacity, maturity, efficiency, response time, lifetime and cycles, power and energy capital cost, time for charging and discharging, and environmental impact. The advantages, disadvantages, and applications of various ESS technologies are provided in Table 2, where the ESS applications are considered as proven, promising or possible for each key application. According to Table 1, two of the ESSs in the electrical category, supercapacitor and SMES, have a higher efficiency rating than any other ESS technologies, and also have lower costs and a lifetime exceeding 20 years. All of the electrical ESSs are used for power quality issues, while the SMES is also an option for RES integration and network stabilisation as indicated in Table 2. The supercapacitor is a promising option for voltage regulation, network stabilisation, and end-user applications, while SMES is suitable for voltage regulation, spinning reserve, and end-user services. For the mechanical category, although the mature ESSs (PHS and CAES) are more efficient and have a longer lifetime than other ESS options, their power cost is higher. In contrast, the cost of energy for PHS and CAES is lower due to the high discharge time, although the opposite is true for FES. Both mechanical ESSs are used for many network applications such as energy management, peak shaving, time shifting, and load leveling.

Another mechanical option, FES, which is in the early phase of commercialisation, has good efficiency, long lifetime (above 15 years) and low power cost and is used for power quality improvement, RES integration, and emergency back-up. Although batteries (electrochemical ESSs) are proven options for most distribution network applications and have long lifetime and good efficiency, some options (e.g., NaS, Li-ion, NiCd, VRB, and ZnBr) are costly. The emerging ESS technologies such as solar fuel (thermochemical ESS) and CES (thermal ESS) have low environmental impacts, while the environmental impact of some other technologies, e.g., PHS, CAES, and batteries, is adverse. Another developing ESS technology in the chemical category, the H<sub>2</sub> Fuel Cell, has almost zero self-discharge and long-term storage capacity as well as being a promising option for most distribution network applications. Despite having some advantages – e.g., lower cost and higher lifetime – and being proven options for energy management applications, the thermal ESSs have slow response times. However, they are promising options for other applications such as peak shaving, time shifting, load levelling, black start, seasonal storage, and network expansion.

The appropriate selection of grid-scale ESSs depends on various factors such as system capacity, required performance, ESS cost and reliability, and type of application. As can be seen from Tables 1, 2, with a higher efficiency and a longer lifetime, the SMES is a proven option for power quality maintenance, RES integration, and network stabilisation, and a promising option for spinning reserve, voltage regulation, and end-user services. In contrast, the thermochemical, chemical, and thermal ESSs are promising storage technologies with

potential for different grid-scale applications. Despite some limitations, batteries are well established ESSs for most of the applications in Table 2. A recent version, the UltraBattery (also known as advanced Lead-acid battery), developed by the Furukawa Battery Co. of Japan and the Commonwealth Scientific and Industrial Research Organisation (CSIRO) of Australia and tested by the U. S. Advanced Lead-Acid Battery Consortium (ALABC), is frequently incorporated in grid-scale applications in the U.S. and Australia as it performs better than other electrochemical ESSs (e.g., Lead-acid) [78,75]. The accumulation of lead sulfate is a well-known barrier to Lead-acid batteries attaining the sustained level of operation required for heavy duty performance: this problem is reduced by incorporating carbon in the UltraBattery. This battery acts as a buffer to tackle the high-rate charge/discharge process by inserting a supercapacitor so that the ESS can operate successfully within a state of charge (SoC) window below 70%, unlike conventional Lead-acid batteries [75,79].

Thus, the optimal choice of ESSs depends on the expected performances, ESS characteristics and application types (as presented in Table 1, 2); however, there must be some trade-offs among different ESS facilities. Despite having lower energy density, the FES, which is in an early commercialisation phase, may be the optimal choice for a distribution network as it offers many advantages such as a low power capital cost, high power and efficiency ratings, fast response, a lifetime exceeding 15 years, and a fast charging time. Moreover, it has no negative environmental impacts and is already used with some important distribution network applications such as power quality improvement, RES integration, and emergency back-up. It is also a promising option for energy management, spinning reserve, network stabilisation, voltage regulation, and end-user applications.

#### 2.4. Smart charging-discharging of ESSs

ESSs need smart charging and discharging protocols to eliminate some problems, e.g., excessive charging or discharging and power compensation failures, even if their energy capacities are unlimited. Control of the SoC of ESSs in distribution network applications is essential. An SoC control strategy is proposed in [80] to facilitate localised control, regulate the SoC of each ESS, exploit available ESS capacities effectively and ensure voltage regulation while evading ESS saturation or depletion for various operational conditions. Appropriate charging and discharging strategies, and adherence to manufacturers' recommendations must be maintained to address the major challenges of ESS deployments, i.e. achieving maximum output, optimal efficiency, and a long lifetime.

Several recent studies have continued to develop suitable charging and discharging protocols for ESSs. An optimal charging and discharging schedule of an ESS is presented in [81] to facilitate peak load shaving in a grid-connected PV system. For the proposed ESS model in Fig. 3, the charging and discharging rules are expressed in Eq. (1) and (2) [82]. This model and charging and discharging strategies are useful for integrating RESs (wind) into the grid and mitigating the intermittency of wind energy and line congestion [82].

Charging strategy:

$$P_n^{IN} = \min\{(F_n^L - C_{RL}), P_{ESS}^{IN}, (E_{MAX} - E_{n-1})/\Delta t\} \quad (1)$$

When line congestion appears ( $F_n^L - C_{RL} > 0$ ) with the charge rate restricted by the  $P_{ESS}^{IN}$  as well as by the ESS availability, only the ESS will be charged.

Discharging strategy:

$$P_n^{OUT} = \min\{(C_{RL} - F_n^L), P_{ESS}^{OUT}, (E_{n-1} - E_{MIN})/\Delta t\} \quad (2)$$

When there is no congestion ( $F_n^L - C_{RL} < 0$ ) and the discharge rate is restricted by the  $P_{ESS}^{OUT}$  as well as by the available line capacity ( $C_{RL} - F_n^L$ ), to avoid new congestion because of discharged power, then only discharging of ESSs will occur. The discharging of ESSs continues on the condition that stored energy is available.

Importantly, in [83], an ESS charging-discharging strategy for low-

**Table 1**  
Comparison of technical characteristics of different types of ESSs along with environmental impact issues.

| ESS Technology             | Available Capacity (MW) | Maturity                         | Efficiency (%)             | Response Time | Lifetime, Years (cycles) | Power Capital Cost (\$/kW) | Energy Capital Cost (\$/kWh) | Charge time  | Discharge time | Environmental impact |
|----------------------------|-------------------------|----------------------------------|----------------------------|---------------|--------------------------|----------------------------|------------------------------|--------------|----------------|----------------------|
| <b>(1) Electrical</b>      |                         |                                  |                            |               |                          |                            |                              |              |                |                      |
| Capacitor                  | 0–0.05                  | Commercialised                   | 60–65                      | ms            | ~ 5 (> 50,000)           | 200–400                    | 500–1000                     | s – hr       | ms – 60 min    | Small                |
| Supercapacitor             | 0–0.3 +                 | Developing                       | 90–95                      | 8 ms          | 20 + (> 100,000)         | 100–450                    | 300–2000                     | s – hr       | ms – 60 min    | None                 |
| SMES                       | 0.1–10                  | Developing                       | 95–98                      | < 100 ms      | 20 + (> 100,000)         | 200–489                    | 1000–72,000                  | min – hr     | ms – 8 s       | Moderate (–ve)       |
| <b>(2) Mechanical</b>      |                         |                                  |                            |               |                          |                            |                              |              |                |                      |
| PHS                        | 100–5000                | Mature                           | 75–85                      | s – min       | 40–60 (> 13,000)         | 2000–4300                  | 5–100                        | hr – months  | 1–24 hr +      | Large (–ve)          |
| CAES (Large-scale)         | 5–1000                  | Mature                           | 70–89                      | 1–15 min      | 20–40 (> 13,000)         | 400–1000                   | 2–120                        | hr – months  | 1–24 hr +      | Large (–ve)          |
| FES                        | 0.1 – 20                | Early commercialised             | 93–95                      | < 4 ms – s    | 15 + (> 100,000)         | 250–350                    | 1000–14,000                  | s – min      | ms – 15 min    | Almost none          |
| <b>(3) Electrochemical</b> |                         |                                  |                            |               |                          |                            |                              |              |                |                      |
| Lead-acid                  | 0–40                    | Mature                           | 70–90                      | 5–10 ms       | 3–15 (2000)              | 300–600                    | 200–400                      | min – days   | s – hr         | Moderate (–ve)       |
| UltraBattery               | 0–36                    | Developing                       | –                          | ~ 5 ms        | 3–15 (3000)              | –                          | 200                          | min – days   | s – hr         | Moderate (–ve)       |
| NaS                        | 0.05–34                 | Commercialised                   | 80–90                      | 1 ms          | 10–15 (2500–4500)        | 1000–3000                  | 300–500                      | s – hr       | s – hr         | Moderate (–ve)       |
| Li-ion                     | 0–100                   | Demonstration                    | 85–90                      | 20 ms – s     | 5–15 (1000–20,000)       | 900–4000                   | 600–3800                     | min – days   | min – hr       | Moderate (–ve)       |
| NiCd                       | 0–40                    | Commercialised                   | 60–65                      | ms            | 10–20 (2000–3500)        | 500–1500                   | 400–2400                     | min – days   | s – hr         | Moderate (–ve)       |
| Metal-air                  | 0–0.01                  | Developing                       | ~ 50                       | ms            | – (100–300)              | 100–250                    | 10–60                        | hr – months  | s – 24 hr +    | Small                |
| VRB                        | 0.03–3                  | Early commercialised             | ~ 85                       | < 1 ms        | 5–10 (12,000 +)          | 600–1500                   | 150–1000                     | hr – months  | s – 10 hr      | Moderate (–ve)       |
| ZnBr                       | 0.05–10                 | Demonstration                    | ~ 75                       | < 1 ms        | 5–10 (2000 +)            | 700–2500                   | 150–1000                     | hr – months  | s – 10 hr      | Moderate (–ve)       |
| <b>(4) Thermochemical</b>  |                         |                                  |                            |               |                          |                            |                              |              |                |                      |
| Solar fuel                 | 0–10                    | Developing                       | ~ 20–30, planned eff. > 54 | –             | – (–)                    | –                          | –                            | hr – months  | 1–24 hr +      | Benign               |
| <b>(5) Chemical</b>        |                         |                                  |                            |               |                          |                            |                              |              |                |                      |
| H <sub>2</sub> Fuel Cell   | 0–58.8                  | Research/developing/<br>marketed | 25–58                      | < 1 s         | 5–20 + (1000–20,000 +)   | 500–10,000                 | 15                           | hr – months  | sec – 24 hr +  | Small                |
| <b>(6) Thermal</b>         |                         |                                  |                            |               |                          |                            |                              |              |                |                      |
| CES                        | 0.1–300                 | Developing                       | 40–50                      | –             | 20–40 (> 13,000)         | 200–300                    | 3–30                         | min – days   | 1–8 hr         | Benign (+ve)         |
| AL-TES                     | 0–5, 1103               | Developing                       | 50–90                      | –             | 10–20 (–)                | –                          | 20–50                        | min – days   | 1–8 hr         | Small                |
| HT-TES                     | 0–60                    | Developed                        | 30–60                      | –             | 5–15 (> 13,000)          | –                          | 30–60                        | min – months | 1–24 hr +      | Small                |

MW = Megawatt, kW = Kilowatt, kWh = Kilowatt hour, eff. = Efficiency, ms = Milliseconds, min = Minutes, s = Seconds, hr = Hours, –ve = Negative, +ve = Positive.

**Table 2**  
Relative advantages, disadvantages, and applications of various ESSs.

| ESS Technology             | Advantages   | Disadvantages                                      | Applications  |                   |                 |            |                   |              |               |               |             |                  |                  |                   |                       |                    |                   |
|----------------------------|--|--|---------------|-------------------|-----------------|------------|-------------------|--------------|---------------|---------------|-------------|------------------|------------------|-------------------|-----------------------|--------------------|-------------------|
|                            |  |  | Power quality | Energy management | RES integration | RE back-up | Emergency back-up | Peak shaving | Time shifting | Load leveling | Black start | Seasonal storage | Spinning reserve | Network expansion | Network stabilisation | Voltage regulation | End-user services |
| <b>(1) Electrical</b>      |  |  |               |                   |                 |            |                   |              |               |               |             |                  |                  |                   |                       |                    |                   |
| Capacitor                  | Fast response, higher cycle life   | Lower capacity, lifetime, and efficiency           | ✓             |                   |                 |            |                   |              |               |               |             |                  |                  |                   |                       |                    |                   |
| Supercapacitor             | Long lifetime and high efficiency  | Toxic and corrosive, low energy density            | ✓             |                   |                 |            |                   |              |               |               |             |                  |                  | ✱                 | ✱                     |                    | ✱                 |
| SMES                       | High power and efficiency, long lifetime, and potential of 2000+ MW capacity | Impact to health for large-scale sites             | ✓             | ✓                 |                 |            |                   |              |               |               |             | ✱                |                  | ✓                 | ✱                     |                    | ✱                 |
| <b>(2) Mechanical</b>      |  |  |               |                   |                 |            |                   |              |               |               |             |                  |                  |                   |                       |                    |                   |
| PHS                        | Higher capacity and lower cost/unit capacity                                 | Disturbance to local wildlife and water level      |               | ✓                 |                 | ✱          |                   | ✓            | ✓             |               | ✱           |                  | ✓                |                   |                       |                    |                   |
| CAES (Large-scale)         | Higher capacity and lower cost/unit capacity                                 | Difficult to select sites for use                  |               |                   | ✱               | ✱          |                   | ✓            | ✓             |               | ✱           |                  | ✱                |                   |                       |                    |                   |
| FES                        | High power and efficiency  | Lower energy density                               | ✓             | ✱                 |                 |            | ✓                 |              |               |               |             | ✱                |                  | ✱                 |                       |                    | ✱                 |
| <b>(3) Electrochemical</b> |  |  |               |                   |                 |            |                   |              |               |               |             |                  |                  |                   |                       |                    |                   |
| Lead-acid                  | Lower capital cost   | Lower energy density                               | ✓             | ✓                 | ✓               | ✓          | ✓                 | ✓            | ✓             | ✓             | ✓           |                  | ✓                | ✓                 | ✓                     |                    | ✓                 |
| UltraBattery               | Lower capital cost and better performance than Lead-acid                     | Lower energy density                               | ✓             | ✓                 | ✓               | ✓          | ✓                 | ✓            | ✓             | ✓             | ✓           |                  | ✱                | ✓                 | ✓                     |                    | ✓                 |
| NaS                        | Higher energy density and efficiency, almost zero self discharge             | High production cost, need recycling for Na        | ✓             | ✓                 | ✓               | ✓          | ✓                 | ✓            | ✓             | ✓             | ✓           |                  | ✓                | ✓                 | ✓                     |                    | ✓                 |
| Li-ion                     | Higher power and energy density, and high efficiency                         | Require recycling of costly Lithium oxide and salt | ✓             | ✓                 | ✓               | ✓          | ✓                 | ✓            | ✓             | ✓             | ✓           |                  | ✓                | ✓                 | ✓                     |                    | ✓                 |
| NiCd                       | Good efficiency, higher power, and energy density                            | Highly toxic                                       | ✓             | ✓                 | ✓               | ✓          | ✓                 | ✓            | ✓             | ✓             | ✓           |                  | ✓                | ✓                 | ✓                     |                    | ✓                 |
| Metal-air                  | Low cost, high energy density, and environment friendly                      | Low cycling time and poor recharge ability         | ✓             | ✓                 |                 |            |                   | ✓            | ✓             | ✓             | ✓           |                  | ✓                | ✓                 | ✓                     |                    | ✓                 |
| VRB                        | High capacity  | Lower power and energy density                     | ✱             | ✓                 | ✓               | ✓          | ✓                 | ✱            | ✱             | ✱             | ✓           |                  | ✱                | ✱                 | ✓                     |                    | ✱                 |

(continued on next page)

Table 2 (continued)

| ESS Technology            | Advantages  | Disadvantages                          | Applications  |                   |                 |            |                   |              |               |               |             |                  |                  |                   |                       |                    |                   |
|---------------------------|---|--|---------------|-------------------|-----------------|------------|-------------------|--------------|---------------|---------------|-------------|------------------|------------------|-------------------|-----------------------|--------------------|-------------------|
|                           |   |  | Power quality | Energy management | RES integration | RE back-up | Emergency back-up | Peak shaving | Time shifting | Load leveling | Black start | Seasonal storage | Spinning reserve | Network expansion | Network stabilisation | Voltage regulation | End-user services |
| ZnBr                      | High capacity   | Costly, low energy density             | ✱             | ✓                 | ✓               | ✓          | ✓                 | ✱            | ✱             | ✱             | ✓           |                  | ✱                | ✱                 | ✓                     | ✱                  |                   |
| <b>(4) Thermochemical</b> |   |  |               |                   |                 |            |                   |              |               |               |             |                  |                  |                   |                       |                    |                   |
| Solar fuel                | High energy density and specific energy, environmentally viable, almost zero self discharge   | Lower efficiency                       |               |                   | ✱               | ✱          | ✱                 | ✱            |               |               |             | ✱                |                  |                   |                       |                    |                   |
| <b>(5) Chemical</b>       |   |  |               |                   |                 |            |                   |              |               |               |             |                  |                  |                   |                       |                    |                   |
| H <sub>2</sub> Fuel Cell  | Almost zero self discharge, long term storage, variety of cell types for various applications | Frequently requires expensive catalyst | ✱             | ✓                 |                 | ✱          | ✱                 | ✱            | ✱             | ✱             | ✱           |                  | ✱                | ✱                 |                       |                    |                   |
| <b>(6) Thermal</b>        |   |  |               |                   |                 |            |                   |              |               |               |             |                  |                  |                   |                       |                    |                   |
| CES                       | High capacity and low cost  | Low efficiency                         | ✓             |                   |                 |            |                   |              | ✱             | ✱             | ✱           |                  | ✱                |                   |                       |                    |                   |
| AL-TES                    | Environmentally sustainable   | Low lifetime                           | ✓             |                   |                 |            |                   | ✱            | ✱             | ✱             | ✱           |                  | ✱                | ✱                 |                       |                    |                   |
| HT-TES                    | Low capital energy cost (\$/kWh)  | Low lifetime and efficiency            | ✓             |                   |                 |            |                   | ✱            | ✱             | ✱             | ✱           |                  | ✱                | ✱                 |                       |                    |                   |

RES = Renewable energy source, RE = Renewable energy, ✓ = Proven, ✱ = Promising, ✱ = Possible

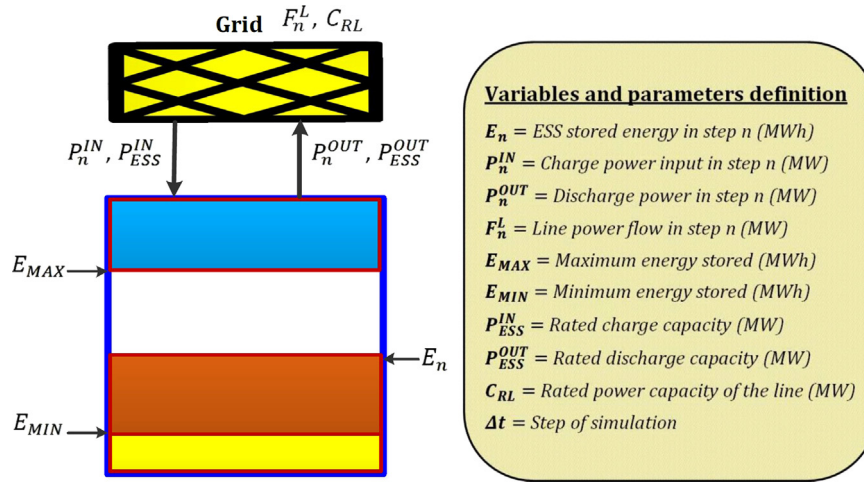


Fig. 3. A grid-connected ESS model.

voltage distribution networks is proposed to mitigate abrupt fluctuations in PV outputs and support peak loads in the evening. In that research, the current SoC status of the ESS and the probable length of charging/discharging periods are considered for effective use of available ESS capacity. With the proposed strategy, the deviation of the SoC of ESSs can also be tracked and adjusted to the desired level. Again, an optimal ESS charging-discharging schedule is developed on an hourly basis to minimise the distribution system's energy losses and mitigate the intermittency of PV-based DG outputs [84]. The optimisation is accomplished by using the genetic algorithm (GA) and the proposed method has great potential for analysis of future ESS applications such as voltage support, peak-load shifting, regulation service, and reliability improvement.

In [85], a real-time, distributed algorithm for an aggregator, coordinating a group of distributed ESSs, is presented to provide a power balancing service to a power grid through charging or discharging. In this research, a modified Lyapunov optimisation framework for real-time power balancing is developed by incorporating some characteristics such as time-varying power imbalance and electricity price, finite battery size constraints, cost of using external energy sources, and battery degradation. The proposed algorithm asymptotically provides optimal performance as the capacity of distributed ESSs increases with quick convergence. However, this research does not deal with the joint optimisation of self-charging and power balancing, which may be a challenging problem. In [60], a three-phase unbalanced distribution optimal power flow optimisation model is developed for optimal operation scheduling of ESSs in distribution networks with RES integration and load fluctuations. In this model, optimal charge/discharge schedules of ESSs are generated while satisfying voltage limits; simulation results reveal reductions in power losses and mitigation of peak demand, i.e. improvement of overall efficiency in the distribution network. However, there is no evaluation of the proposed method on a larger system and in meshed networks.

A new framework – flexible distribution of energy and storage resources – is developed in [86–88], which is inspired by the V-shape formations of flocks of birds [89,90] and the peloton/echelon formations of cycling racing teams [91–93]. In the case of V-shape formations, the birds or cyclists change their positions continuously to save energy, otherwise the leading bird or cyclist becomes exhausted sooner than its drafting counterparts. By using these concepts, intelligent charging and discharging protocols are developed in that framework to save ESS energy and lifetime. However, this framework is only developed for micro-grids by considering the distance to a placed ESS as a controlling factor and not extended to distribution grids.

The uncontrolled charging and discharging affect the cycle life of ESSs and are responsible for the capacity fade phenomenon known as ESS ageing caused with the decrease of ESSs' deliverable capacity

[94,95]. Generally, the cycle life of an ESS indicates the number of cycling times with allowable capacity fading of lower than 80% of its nominal value [96,97]. The results of applying the flexible distribution of energy and storage resources approach in [88] show that ESS lifetime depends on the cycling sequence, pattern, and occurrence and can be extended by 76% of the baseline (which is 86% in an ideal case). As ESSs are expensive devices for distribution network applications, ESS lifetime extension is a critical issue. Smart charging and discharging strategies can save energy, facilitate optimal ESS efficiency achievement, and ensure a longer lifetime.

### 3. Optimal ESS placement, sizing, and operation, and power quality issues in distribution networks

#### 3.1. Determining optimal ESS locations

The ESS is a particularly important tool that will increasingly become available to network operators and planners. There are many ESS options to be explored in terms of technical characteristics and application benefits for the distribution network, as tabulated in Table 1 and 2. The large capital investment required makes the adoption of an ESS a significant step for a network, and their installation must therefore be part of an extensive smartening of distribution networks [23]. To maximise the benefits from an ESS operation, it is crucial to determine the optimal ESS locations in a distribution network. Alongside the technical benefits of ESS usage such as improved voltage and power quality, utility system reliability, reduced power losses, and relieved distribution congestion [23,57,16,14,34], the use of ESSs in non-optimal locations can lead to reduced network performance [98].

Although an ESS can be installed anywhere in a distribution system, appropriate placement can facilitate optimal ESS operation for power quality improvement, peak demand mitigation, overall network cost reduction, RES integration, and system effectiveness. The determination of optimal ESS locations in a distribution network can involve one or more optimisation problems depending on the benefits targeted. To facilitate this determination process, a comprehensive survey is indispensable. Various types of distribution system data should be collected for a particular distribution network prior to analysis with a powerful decision-making tool. Appropriate tools could include DiGSILENT PowerFactory, MATLAB, Gurobi, Powerworld, CYME, GridLAB-D, OpenDSS, PSCAD, ISM-DEW (integrated system model- distributed engineering workstation), and EMTP-RV (the electromagnetic transient program- restructured version). The DiGSILENT PowerFactory provides useful solutions for distribution network problems including system design, data handling, modelling and optimisation capabilities, and grid interactions skill in a multi-user environment [99]. The suitability of



DIgSILENT PowerFactory has been demonstrated in several relevant studies [100–109], where it has been utilised on its own and also in tandem with other tools such as MATLAB. MATLAB is also a widely used tool for distribution network analyses such as power-flow analysis with a high DG penetration [110], fault analysis [111], development of a new algorithm (for customer classification) and load profiling technique [112], optimal grid sizing and control with ESSs [113], and optimal placement, sizing, and operation of ESSs [114–116,32]. For simulation packages in MATLAB, MATPOWER offers solutions for complex optimal power flow (OPF) problems for both large-scale AC and DC [117], while PSAT provides scope for designing and analysing distribution networks [118]. Moreover, the flexibility of MATLAB is apparent from its capacity for integration with other software such as DIgSILENT PowerFactory [104,105,109,107,108], Gurobi [119,120], OpenDSS [121–123], PSCAD [124], ISM-DEW [123], and GridLAB-D [125]. Gurobi is also used for various ESS applications in distribution networks such as ESS allocation, scheduling, operation, and control [119,126,120]. PSCAD can be employed for power system analysis, dynamic distribution network modelling, and RES modelling [124,127,128].

Similarly, other software can also be used to deal with distribution network problems. Powerworld is used for power flow analysis [129] and the optimal placement and sizing of DG [130]. The CYMDIST (Cooper Power Systems distribution simulator), a part of CYME software, is suggested in [131,123] for planning, modelling, and simulating a distribution network. GridLAB-D, OpenDSS, ISM-DEW, and EMT-P are also used [123,132–134,121,135,122,136,137] for the analysis of various problems in distribution networks as well as smart grids. Thus, a specific tool should be selected depending on the distribution network challenges. This can be employed for analysis independently or together with other software.

### 3.2. Optimal ESS sizing

Because of the crucial role played by the ESSs, their sizing is essential for guaranteeing the correct operation of distribution grids. From both economic and security viewpoints, an accurate and practical ESS model would enhance modelling of system operation [138,139]. Optimally sizing the ESS involves finding the optimal ESS power and energy capacities in order to minimise the operating cost of the distribution grid while still meeting performance targets. The capital cost of ESSs is an important part of calculating the distribution grid's operating cost which in turn depends on the payback period of the investment, so the lifetime of ESSs is crucial. The number of cycles and the SoC at which the ESS operates are the two main factors that affect the lifetime of batteries [140]. The estimated lifetime of an ESS is used to calculate the cost associated with the ESS in [114], whereas in [140,141] lifetime is determined according to prediction models. Table 3 classifies the research on optimal ESS sizing from the viewpoints of grid scenario, applied strategies of sizing, ESS technologies used, advantages, and research scope. Most of these studies [142–149] consider a specific ESS technology for sizing, while a few [150,151] are ESS technology neutral. The main research focus is to minimise cost, integrate RESs and analyse their effects, and achieve network benefits. However, there is also some scope for future research, as identified in Table 3.

Optimal ESS sizing should be established for a distribution grid, as large ESSs impose higher investment and maintenance costs on the grid while small ESSs may not provide the desired economic benefits and flexibility or meet predefined reliability objectives for the grid. The optimal ESS sizing for a distribution network should comprise all costs directly related to network benefits. For instance, if RESs are integrated into the distribution networks, it is necessary to include fixed operation and maintenance costs for integrated RESs in ESS sizing. Moreover, selecting an ESS for optimal sizing and comparing it with alternative ESSs in terms of cost and performance can help to identify an

appropriate ESS option for a location in a distribution network.

### 3.3. Literature review on ESS placement and operation

In this section, the existing research on ESS placement and operation problems is classified from the viewpoints of grid scenario, objectives to be fulfilled, algorithm and strategies used, testing bus, and various advantages and limitations. In addition, the section details whether individual pieces of research work specify ESS technology or not. Table 4 summarises the relevant literature on ESS placement and operation problems (as placement and operation are interrelated) from various viewpoints, based on different techniques, scenarios, and limitations. The optimal placement and operation of an ESS can help to adjust the power flow and reduce power loss in distribution networks. This is particularly useful for balancing generation with consumption and maintaining system stability [152].

From the perspective of targeted objectives, most of the literature [153–168,114,169,98,170,115,171,116,172–175,32] focuses on finding optimum ESS locations in a distribution network, while optimal operation is targeted by [176,177,126,178,179,167,180,168,114,169,181,182,115,183–185]. Optimal ESS scheduling is accomplished in [186] to improve voltage profile and minimise network losses and cost (in terms of energy). The optimal ESS placement embedded with network reconfiguration is carried out by [187,119,188], where the power flow is optimised [187], network security and losses are further minimised [119], and RES integration is maximised [188]. However, more optimal reconfiguration of distribution networks can be introduced for better network performance expectations. For optimisation, different types of algorithms, e.g., dynamic programming, GA, particle swarm optimisation (PSO), fuzzy PSO, are employed; however, no comparisons of such heuristic methods are presented in the literature except [160] (which is not a comprehensive comparison), and hybrids of these algorithms are reported in only a few publications [177,162,163,160,170,115,172,174]. Software such as MATLAB, PSFL, OpenDSS, CPLEX, GAMS, Gurobi, and DIgSILENT PowerFactory is used for system simulation and modelling, although MATLAB is the major choice. Many researchers use a specific test bus system such as IEEE 13, 14, 15, 24, 30, 33, 34, 37, 39, 84, 119, 123, 906, or 8500 to verify system performance instead of general test systems. From the ESS technology viewpoint, batteries (single or hybrid) are widely used among other ESS options and the comparative investigation of various ESS types is presented in [176,156,157,160,32,180,115,171–173] to provide better outcomes for large-scale capital investment in distribution networks.

Notably, to ensure sustainable energy supply with RES integration, wind is considered in [159,157,162,169–171,115,172,183,184,174,185], PV is integrated in [189,119,176,120,178,167,166,177,186,114,182,173,116,98], and both (or generic RESs) are also incorporated in some studies, e.g., [187,177,126,188,158,154,156]. Though generation from RESs significantly affects power quality due to intermittent nature, overall mitigation of this issue is not considered in the RES integrated distribution network by the literature in Table 4. Some power issues such as voltage fluctuations or deviations, frequency deviations, over-voltage, and undervoltage are addressed in some studies [119,154,155,190,186,188,158,161,166,162,163,191,192,170,114,193]. However, there are still opportunities for in-depth studies addressing other power quality issues such as flicker, harmonic distortion, voltage sag, voltage swell, short or long term interruption, and oscillatory transients. Moreover, the impact on the lifetime of ESSs, after optimal placement and operation, is addressed by very few research works [176,158,98,114,181,173].

To have sustainable solutions for the optimal ESS placement problem in an RES integrated distribution network, various network issues, including the uncertainties of RES generation and loads, must be considered and modelled. However, these uncertainties have only been taken into account in a few studies [163,166,119,159,120,160,162,

**Table 3**  
Review of literature based on optimal sizing and strategies of ESSs.

| Ref.  | Grid Scenario                                   | Sizing strategies   | ESS types  | Advantages  | Research scopes  |
|-------|---|---|--|---|--|
| [142] | A wind farm-ESS system                          | Non-dominated sorting genetic algorithm II (NSGA-II)  | Lead-acid  | Good cycle control, improvement of ESS lifetime   | Incorporation of other ESSs, e.g., UltraBattery, and performance evaluation and comparison; application of other hybrid optimisation approaches  |
| [143] | A wind-ESS based hybrid power system            | Auto regression moving average (ARMA) modelling technique, sequential Monte Carlo simulation (MCS), MSAES based on the Fischer-Burmeister algorithm | NiCd and Li-ion                                      | Providing flexibility to decision makers for optimal ESS sizing under different values of load shifting or reliability levels         | The geographical constraints for ESS sizing are not considered, cost functions can be developed for other ESS technologies with different optimisation techniques                                      |
| [150] | A distribution network                          | Multi-period AC optimal power flow (OPF) and bi-level AC OPF iterative processes  | Not specified  | Reduction of curtailment from RESs; management of congestion and voltages   | Hybrid RES consideration, performance investigation of different types of ESSs considering effects of charging/discharging cycles, technical parameters, and lifetime                                  |
| [13]  | –   | Pareto-optimal sizing   | Hybrid ESS-batteries and SCap                        | Applicable to solar power and self usage, stable performance, can be converted to LP with reduced computation time                    | Other ESS involvement for hybridisation, applying other optimisation approaches  |
| [151] | A distribution grid                             | GAMS modelling language and CPLEX solver  | Technology neutral but based on Lead-acid and Li-ion | Time shifting and arbitrage, energy related CAPEX reduction, benchmark for aggregator profitability                                   | Analysis can be done for power applications, incentive mechanism design ensuring cost-effectiveness of photovoltaic (PV) use and distribution grid design  |
| [144] | A modified General Electric Distribution System | New energy management system, MATLAB simulation   | Li-ion phosphate                                     | Developing cost-benefit ESS size with high PV penetration, facilitating peak load shaving, voltage regulation, and peaking generation | Can be applied to other distribution systems (large-scale), the approach can be employed to determine ESS cost-benefit size for other applications such as spinning reserve and frequency regulations. |
| [145] | A distribution Grid (unbalanced)                | Modelled in GAMS, simple branch and bound (SBB) solver  | VR and NaS   | Maximising the difference between the discharging and charging costs of an ESS; minimisation of investment cost                       | Cost functions can be developed for other ESS technologies, application of other algorithms and strategies   |
| [146] | A medium voltage smart grid                     | A new cost-based optimisation strategy, SQP-based inner algorithm   | Redox batteries (VR)                                 | Facilitating RES integration, deferring network upgrading, and offering VAR regulation  | Option for multi-objective optimisation considering different technical and economic objectives of ESSs, DG penetration, and deployment of ESSs and capacitors   |
| [147] | Large/small-scale grids with PV generation      | Markov-chain-based ESS model  | Li-ion   | Decreasing system cost, ensuring adequate power availability, tracking the energy states of PV-ESS environment                        | Can be applied for wind power plants, development of a real-time availability estimator with real-time SoC or energy level   |
| [148] | Large-scale wind farm in utility grid           | Application of four strategies - simple, fuzzy, simple ANN, and advanced ANN with a comparison  | ZnBr   | Increase in output predictability of wind power plant, decrease in wind integration cost  | Other sizing topologies may be selected and compared with advanced ANN, analysis can be focused on PV or hybrid RES integration  |
| [149] | Stand-alone PV systems weakly connected to grid | Particle swarm optimisation (PSO)   | Lead-acid, Ni-Cd, and H <sub>2</sub> Storage chain   | Minimisation of total levelised cost, achievement of cost benefits for ESS uses in both short term and mid term                       | Other optimisation approaches can be applied, research can be conducted with other ESS technologies  |

Ref. = Reference, MSAES = Modified self-adaptive evolutionary solver, SCap = Supercapacitors, LP = Linear programming, GAMS = General algebraic modelling system, CPLEX = Simplex method as implemented in the C programming language, CAPEX = Capital expenditure, SQP = Sequential quadratic programming, DG = Distributed generation, ANN = Artificial neural network, VAR = A unit of reactive power.

**Table 4**  
Review of literature based on optimal placement and operation of ESSs.

| Literature (chronological) | Grid Scenario                               | Targeted Objectives   | Applied Algorithm and Strategies  | Test bus  | ESS types                                       | Advantages  | Limitations/future research opportunities   |
|----------------------------|---|---|---|---|---|---|---|
| [119]                      | Active distribution networks                | Optimal allocation of distributed ESSs and grid reconfiguration   | Convex optimal power flow (OPF), Gurobi, and MATLAB interface- YALMIP used for implementation                                     | 6-bus and 70-bus  | Not specified                                   | Minimisation of voltage deviation, line congestion, energy supply and ESS investment costs, and network losses                                  | Only photovoltaic (PV) is considered as an RES, and more optimal grid reconfiguration is also possible  |
| [167]                      | Active distribution grids                   | ESS operation and planning using a non-parametric chance-constrained (NPCC) optimisation approach   | Mixed integer linear programming (MILP), Gaussian approximations, Monte Carlo simulation (MCS), NPCC, scenario based optimisation | Radial 12-bus, IEEE 13                                  | Li-ion  | Modelling of electric vehicles (EVs) and DG uncertainties, ESS operation and installation cost minimisation                                     | Generalisation of the proposed method for current chance-constraints is not investigated, the slack bus voltage is considered as fixed which fluctuates practically; this approach can be applied to other non-ESS scenarios, addressing the inaccuracy of line current chance and ESS energy constraints |
| [187]                      | Soft open point based distribution networks | Optimal determination of distributed ESS locations and energy/power capacities including network reconfiguration and DG reactive power capability | MISOCP, implemented in MATLAB interface- YALMIP   | IEEE 33 (modified)                                      | Not specified                                   | Improved utilisation of RES generation, reduction of network losses, providing supports to decision makers for optimal ESS sizing and placement | Power quality issues due to RES integration are not addressed, investigation can be done with more optimal network reconfiguration  |
| [153]                      | Distribution networks                       | Optimal ESS placement and sizing  | Analytical modelling, OPF, and DistFlow modelling   | IEEE 123 (modified)                                     | Not specified                                   | Energy loss minimisation  | More mathematical proof of radial networks, development of more realistic models, investigations on more complicated spatial structure of background injections at buses  |
| [176]                      | Low voltage (LV) distribution grids         | Modelling and optimal operation of distributed ESSs   | Multi-period AC-OPF, linearised AC-OPF, model predictive control (MPC), MLIP, and CPLEX   | –   | Li-ion for two technologies Li-CoO2 and LiFePO4 | 30% reduction of ESS losses, real time control of ESSs, minimisation of ESS degradation, and maximisation of PV utilisation                     | Power quality issues can be investigated with other ESS types   |
| [177]                      | Distribution networks                       | Multi-objective energy management with ESSs   | Hybrid of grey wolf optimiser and PSO, pareto-optimal and fuzzy decision making strategies, MATLAB                                | IEEE 84   | Batteries                                       | Operational cost reduction and reliability improvement  | RES uncertainties are not considered, performance indices other than reliability can be addressed   |
| [154]                      | LV radial distribution networks             | Optimal allocation of ESSs (ESS number, locations, and sizes)   | Multi-period OPF, clustering and sensitivity analysis (CSA), CVX modelling toolbox, and SeDuMi solver                             | IEEE 34 (modified), Italian 17-bus, 200 random networks | Not Specified                                   | Prevention of under and overvoltages, minimisation of total network costs (ESS costs and network losses)  | Appropriate ESS control algorithms to be applied in real-time network operation can be investigated   |

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Table 4 (continued)

| Literature (chronological) | Grid Scenario                     | Targeted Objectives  | Applied Algorithm and Strategies  | Test bus                        | ESS types              | Advantages   | Limitations/future research opportunities  |
|----------------------------|-----------------------------------|--|---|---------------------------------|------------------------|--|--|
| [155]                      | Distribution networks             | Optimal DG allocation and ESS integration  | Loss sensitivity factor approach, multi-objective ant lion optimiser, grey relation projection theory, chance-constrained programming, and probabilistic power flow | PG & E 69-bus                   | Not specified          | Improvement of renewable DG output, minimisation of line losses, maximisation of investment benefits and voltage stability                   | Investigation with more focus on optimal distributed ESS allocation can be carried out, RES and load uncertainty consideration, hybrid ESS incorporation |
| [190]                      | Active distribution networks      | Decentralised real time control of distribution networks using ESSs                    | Multi-agent system (MAS), clustered real time model based control, MATLAB, and YALMIP optimiser   | IEEE 13                         | Li-Titanate            | Good voltage support and line congestion management, feasible voltage and current profiles   | optimal distributed ESSs allocation with larger number of buses can be investigated  |
| [188]                      | Distribution systems              | Optimal ESS deployment and network reconfiguration                                     | Stochastic MILP   | IEEE 119                        | Not specified          | Overall network cost minimisation, voltage profile improvement, system loss minimisation   | Frequency regulation, flicker mitigation, and other power quality issues can be addressed  |
| [156]                      | Distribution systems              | Optimal allocation of ESSs   | A game-theoretic multi-agent approach   | IEEE 15 (radial)                | Lead-acid and Li-ion   | Interaction between ESSs, achievement of Nash equilibrium, improvement and risk mitigation of energy transaction mechanism for energy agents | Other distribution network performance indices, e.g., voltage profile and power quality improvement are not investigated                                 |
| [189]                      | A distribution system             | Development of a controller for real-time operation of grid-connected distributed ESSs | Markov chain process for system modelling and MCS using SimPower toolbox of MATLAB  | Canadian urban benchmark system | Not specified          | Enhancement of stochastic stability of distributed ESSs  | Only PV is considered as an RES and if wind is considered then the flicker issue can be investigated   |
| [126]                      | Active distribution systems       | Scheduling and operation of mobile ESSs  | PSO, energy management system, MISOP, Gurobi  | 41-bus (radial)                 | Batteries              | Cost minimisation of imported grid power and profit maximisation of network operators, voltage supports                                      | Power quality issues can be investigated for mobile ESSs, application of hybrid meta-heuristic optimisation approaches                                   |
| [157]                      | Distribution networks             | Optimal ESS allocation   | GA combined with linear-programming (LP) solver, a sequential MCS   | 33-bus (radial)                 | Lead-acid, VR, and NaS | Cost reduction regarding ESS installation, maintenance, interruption, system upgrade costs, and energy losses                                | Mitigation of power quality issues and improvement of distribution system reliability are not investigated   |
| [193]                      | A modified 4 area power system    | Coordinated control of a grid-connected battery ESS operated with a wind power plant   | A coordinated control strategy implemented in FESTIV, PSIF dynamic simulation software, and MATLAB/Simulink   | 18-bus                          | Li-ion                 | Multi-scale frequency support  | Other power quality issues such as flicker, voltage deviation, overvoltage, and undervoltage can be investigated   |
| [158]                      | European LV distribution networks | Optimal allocation and sizing of ESSs integrating RESs                                 | Non-dominated sorting genetic algorithm II (NSGA-II)  | IEEE 906                        | Batteries              | Voltage profile improvement, DG and ESS cost reduction, ESS lifetime maximisation  | Overall power quality improvement is not investigated  |

(continued on next page)

Table 4 (continued)

| Literature (chronological) | Grid Scenario                                 | Targeted Objectives   | Applied Algorithm and Strategies   | Test bus                    | ESS types     | Advantages   | Limitations/future research opportunities  |
|----------------------------|---|---|--|-----------------------------|---------------|--|--|
| [165]                      | Active distribution networks                  | Optimal allocation, sizing, and operation of large-scale ESSs in RES-penetrated scenarios           | Dynamic programming optimisation algorithm and a mathematical framework  | 13-bus real system of China | VRB           | Maximising RES consumption and ESS benefits, optimising ESS costs  | Voltage profile and power quality investigations can be carried out  |
| [178]                      | A PV-enhanced distribution network            | Steady-state operation of ESSs  | ESS charging-discharging strategy with the incorporation of a load factor, developed in OpenDSS and Digsilent PowerFactory | IEEE 37                     | Batteries     | Reduction of peak load and quantification of power generation and voltage intermittency  | A more adaptive control strategy can be employed, energy management systems and the communication link between ESSs and PVs can be analysed      |
| [164]                      | Distribution networks                         | Optimal ESS integration (ESS number, sizes, and locations)  | NSGA-II and Pareto dominance concept   | 94-bus (radial)             | Not specified | Network reliability improvement (i.e. SAIDI and MAIFI), equipment cost minimisation  | Modelling of specific ESS types is not presented, other reliability indices, e.g., SAIFI, CAIFI, ASIFI, ASAI, CTDAI, and CAIDI are not addressed |
| [120]                      | A Distribution grid with high RES penetration | Control of ESSs to track and shave power  | MPC using MATLAB and Gurobi  | –                           | Not specified | Controlling and smoothing of net power profile exchanged with the grid   | A more theoretical assessment of RES imbalance impact on the control system performance and field testing works can be accomplished              |
| [161]                      | Distribution systems                          | Sizing and siting of ESSs   | GA, LP, OpenDSS  | IEEE 8500                   | Batteries     | Peak demand minimisation, voltage fluctuation mitigation   | Application of other optimisation approaches, specific ESS technology is not addressed and modelled, power quality issues are not investigated   |
| [166]                      | Distribution networks                         | Multiple ESS planning (location, size, and operational characteristics) using cost benefit analysis | Optimal power factor approach, load following control method, and GA toolbox in MATLAB                                     | 33-bus (radial)             | Not specified | Maximisation of total net present value (NPV), improvement of load factors and voltage profiles                                | More investigations for power quality improvement using other optimisation approaches can be targeted  |
| [179]                      | Smart grid                                    | Optimal ESS operation addressing real-time pricing  | Integer coded GA, Auto regression moving average (ARMA) modelling technique, MATLAB  | –                           | Lead-acid     | Minimisation of daily net costs  | Optimisation parameters other than real time pricing can be addressed and analysed   |
| [159]                      | Wind penetrated power systems                 | Optimal ESS allocation based on sensitivity analysis  | Multi-period AC OPF, MATLAB  | IEEE 14 and IEEE 118        | Not specified | Minimisation of costs, power losses and wind power curtailment, maximisation of line congestion mitigation and system benefits | Power quality issues are not investigated  |
| [162]                      | A tap-changer-equipped distribution network   | Optimal ESS planning (location, capacity, and power rating) including EVs, capacitors, and wind DG  | 2 × 3 × 5 Point estimation method (PEM), modified hybrid tabu search (TS) and PSO approach, MCS, probabilistic OPF, MATLAB | 21-bus                      | Batteries     | Cost minimisation including dispatching RESs, peak shaving, reliability improvement, and better voltage regulation             | More analysis for reliability improvement by measuring various indices (e.g., SAIDI and SAIFI), measurement of power quality                     |

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Table 4 (continued)

| Literature (chronological) | Grid Scenario                                     | Targeted Objectives  | Applied Algorithm and Strategies   | Test bus               | ESS types  | Advantages  | Limitations/future research opportunities   |
|----------------------------|---|--|--|------------------------|--|---|---|
| [194]                      | A power distribution system                       | Application of mobile ESSs with RES penetration                                | Markov models, MCS, MATLAB   | IEEE 15, modified RBTS | Batteries  | Improvement of system reliability   | Optimal planning of mobile ESSs considering other optimisation parameters such as demand management, line loading, and power quality is also demanding<br>Power quality issues are not considered                                   |
| [160]                      | Distribution networks                             | Optimal ESS allocation with high wind penetration                              | MCS, hybrid approach of MCS and DE, Multiperiod AC OPF, MATLAB   | IEEE 15                | Lead-acid and ZnBr                                     | Minimisation of investment and operation costs  |   |
| [192]                      | LV radial distribution networks                   | Distributed control of ESSs with high PV penetration                           | A hybrid approach of local droop-based and distributed consensus controls implemented in Matlab/Simulink                         | 7-bus                  | Batteries  | Mitigation of voltage fluctuations  | The proposed control approach can be applied to solve other power quality issues and improve distribution network performance   |
| [191]                      | A Korean distribution system                      | Coordinated control of distributed ESSs  | Coordinated control algorithm implemented in electromagnetic transient program/alternative transient program draw (EMTP/ATPDraw) | –                      | Li-ion   | Reduction of voltage and frequency deviations   | RES integration and other power quality issues, e.g., flicker and interruptions (short or long) are not considered  |
| [186]                      | European medium voltage (MV) distribution network | Optimal ESS scheduling   | Markov chain decision process, MATPOWER  | 14-bus                 | Not specified  | Voltage profile improvement, cost minimisation in terms of energy and network losses  | Investigations need for different network scenarios having larger solar DG or multiple ESSs   |
| [163]                      | An active distribution network                    | Optimal ESS planning (location, capacity, and power rating)                    | PEM, Hybrid TS-PSO approach, OPF, probabilistic load flow  | 21-bus                 | ZnBr   | Overall cost minimisation including ESS, O&M, reliability and constraints violation costs, peak shaving, better voltage regulation, and enhanced reliability<br>Loss reduction in distribution grids, economically beneficial | The proposed approach can be applied to the real sized systems using some other modification strategies, e.g., sensitivity analysis<br>Power quality issues after the placement and RES-integrated ESS placement are not considered |
| [180]                      | Distribution grids                                | Effects of ESS inclusion on grid efficiency                                    | Dynamic programming optimisation   | –                      | UltraBattery, Lead-acid with CEE, VR, Li-ion, and CAES | Minimising generation costs   | Fixed installation costs are neglected during optimisation and ESS applications to renewable generation at faster time-scales are not studied   |
| [168]                      | A power network                                   | Optimal placement and control of ESSs  | Mathematical modelling with deep analysis  | –                      | Not specified  |   | Adaptive management system for ESSs, reactive power management for voltage profile and feeder capacity improvement are not investigated   |
| [114]                      | A distribution network                            | Optimal ESS allocation and operation for improving load and DG hosting ability | Cost-based multi-objective optimisation strategy by MATLAB   | IEEE 33                | Batteries (no specific types)                          | Power loss and peak demand reductions along with better voltage regulation  | (continued on next page)  |

Table 4 (continued)

| Literature (chronological) | Grid Scenario                                    | Targeted Objectives  | Applied Algorithm and Strategies  | Test bus                                       | ESS types                   | Advantages  | Limitations/future research opportunities  |
|----------------------------|--|--|---|--|-----------------------------|---|--|
| [169]                      | An IEEE benchmark radial distribution system     | Determining optimum ESS location and size, and optimal ESS operation with wind integration   | MISOCP model combining unit commitment and AC-OPF, MATLAB toolbox- YALMIP used for implementation | IEEE 34  | Not specified               | Spinning reserve supports for variable wind power, peak demand mitigation   | Power quality issues are not addressed   |
| [181]                      | Smart grid with grid-scale ESSs                  | Characterisation of optimal value-lifetime performance pair for ESSs   | Constrained stochastic shortest path (CSP), Pareto optimal approach                               | –  | Battery                     | Balancing the economic value and lifetime of ESSs, energy arbitrage application of ESSs under dynamic pricing   | Although, the analysis is done for four types of batteries, the ESS types are not specified                          |
| [98]                       | A distribution network                           | Optimal ESS installation site and capacity determination   | A novel bi-level optimisation solution algorithm, OPF, and GA                                     | IEEE 33 (modified)                             | Battery                     | Minimisation of total NPV by integrating DG   | Analysis is not accomplished with specific ESS types; other optimisation approaches can be applied                   |
| [170]                      | A wind power distribution system                 | Sitting and sizing of ESSs given the uncertainty of wind power   | Hybrid multi-objective PSO by incorporating NSGA-II and a probabilistic load flow technique; SPEM | IEEE 30  | Not Specified               | Power system cost minimisation and improvement of voltage profiles  | Impact on ESS lifetime after ESS placement is not studied  |
| [182]                      | A radial distribution network                    | Minimising overall cost of energy (purchased from dispatchable DG and distribution substation) by optimum ESS operation  | Modelling in MISOCP and MILP; implementation by AMPL and CPLEX                                    | 11-node test and 42-node real system           | Not specified               | Reduction of total energy cost, facilitation of DG and RES integration  | Research is not carried out on specific ESSs with performance comparison of various ESSs                             |
| [115]                      | Distribution systems                             | Determination of optimal ESS location and size; optimal ESS operation for load management  | GA combined with LP solver, a sequential MCS, MATLAB optimisation toolbox                         | 33-bus (radial)                                | Lead-acid, VR, and NaS      | Minimisation of NPV and total costs while maximising system benefits; benefits of annual arbitrage  | Power quality and distribution system reliability improvement are not investigated                                   |
| [171]                      | A large-scale power system with wind penetration | Optimal ESS allocation and operation   | GA-based numerical algorithm to solve bi-level programming-based model                            | IEEE 39 (modified) and a regional bus of China | PHS, flow batteries         | Facilitating the integration of large-scale wind power, verifying PHS as an ideal ESS for wind integration  | Other ESS technologies, e.g., Li-ion, Ultrabattery, Lead-acid, SMES, and FES can be considered for better comparison |
| [116]                      | Active distribution networks                     | Optimal ESS siting and sizing by handling voltage deviations, line congestion, cost of supplying loads and ESSs, network losses, load curtailment, and stochasticity of RESs and loads | AC-OPF and MISOCP, YALMIP-MATLAB interface  | IEEE 34  | Not specified               | Mitigation of voltage deviations and improvement of supply quality, elimination of load curtailment and line congestions, minimisation of network cost and electricity cost | The analysis is not carried out with specific ESS technologies   |
| [172]                      | Distribution systems                             | Optimal ESS allocation and determination of loads to be shed, network reliability improvement  | GA combined with LP solver, a sequential MCS  | 33-bus (radial)                                | Lead-acid, CAS, NaS, and VR | Minimisation of interruption cost and improvement of distribution system reliability, annual cost reduction   | Wind is the only RES considered as DG  |

(continued on next page)

Table 4 (continued)

| Literature (chronological) | Grid Scenario   | Targeted Objectives   | Applied Algorithm and Strategies   | Test bus                         | ESS types                           | Advantages  | Limitations/future research opportunities   |
|----------------------------|---|---|--|----------------------------------|-------------------------------------|---|---|
| [183]                      | A power grid  | Optimal ESS operation and picking out the optimal energy and reserve bids for ESSs considering intermittent nature of RESs to market prices | Optimal bidding mechanism, two tractable design approaches   | IEEE 24 (modified)               | Li-ion                              | Ensuring the profitability of ESS investment  | For RES generation, only wind is considered; the suitability of other ESS technologies is not analysed  |
| [184]                      | A grid connected wind power plant                     | Adaptation of optimal ESS operation (for wind energy time shifting) policy to maximise the plant profit                                     | Stochastic dynamic programming framework, inhomogeneous Markov model, objective function approximation, MCS, CPLEX | –                                | CAES                                | Considerably higher profit compared to fixed policy                                 | ESS options (e.g., batteries, flywheel) with rapid response time are not employed, ESS application to frequency regulation and impact of output power on market prices are not analysed |
| [173]                      | A radial distribution network                         | Optimal allocation of ESSs to mitigate risks for distribution companies (DISCOs)  | Fuzzy PSO (FPSO) and a cost-benefit analysis method  | IEEE 15                          | Li-ion and Lead-acid                | Maximising the DISCO's profit from energy transactions and operational cost savings | Power quality issues are not considered   |
| [174]                      | A deregulated power system with high wind penetration | Optimal placement of ESSs to minimise costs   | Market-based probabilistic OPF, GA, an energy arbitrage model  | IEEE 24                          | CAES                                | Maximum utilisation of wind power, minimisation of hourly social cost               | The applicability of various ESS technologies applicable to RES integration is not studied  |
| [185]                      | A distribution network                                | Optimal and flexible ESS operation to maximise the profit compared to fixed ESS operation   | A two stage framework- (1) optimisation of integer variables (2) active-reactive OPF problem, MATLAB, GAMS         | 41-bus rural network             | Battery                             | Achievement of higher profit than fixed ESS operation, price reduction              | More than one ESS cycling is not allowed, only wind is considered as an RES, ESS types are not specified  |
| [175]                      | A distribution network                                | To minimise the cost by introducing standby ESSs  | PSO, Digsilent PowerFactory  | –                                | Battery and fuel cell               | Cost efficiency   | Impacts of grid configuration, load priority, load growth, and cost of optimum placement are not studied  |
| [32]                       | A distribution grid with high wind penetration        | Optimal ESS allocation to maximise the benefits for the utility and DG owner  | ARMA modelling technique, MATLAB, IEEE-RTS   | 41-bus rural distribution system | Lead-acid, VRLA, NaS, ZnBr, and VRB | Minimisation of annual electricity cost   | Not all possible ESS benefits for the utility (e.g., peak shaving and reliability enhancement) are considered   |

FESTIV = Flexible energy scheduling tool for integrating variable generation, PSIF = General electric's positive sequence load flow, O&M = Operation and maintenance, PSO = Particle swarm optimisation.

MISOCP = Mixed integer second order cone programming, CVX = Matlab-based modelling system for convex optimisation, SeDuMi = A linear/quadratic/semidefinite solver for Matlab and Octave.

RBTS = Roy Billinton test system, GA = Genetic algorithm, DE = Differential evaluation, DG = Distributed generation, CEF = Carbon-enhanced electrode, VRLA = Valve-regulated Lead-acid.

AC-OPF = AC optimal power flow, RTS = Reliability test system, CPLEX = Simplex method as implemented in the C programming language.

154,167,156,170,115,116,172,184,174,185]. In [170,184,174], the uncertainty of wind generation has been considered and modelled by different techniques. In [170], the uncertainty of wind generation is considered for the formulation of cost probability optimisation problem and discretised by the 5-point estimation method (5PEM), while the 2PEM is employed by [174]. Wind uncertainty, along with price uncertainty, is handled by a stochastic dynamic programming technique in [184]. In contrast, the load demand uncertainty in [115,172] is presumed to follow the hourly IEEE-reliability test system load-shape rather than being characterised by special techniques; however, the researchers employ a probabilistic approach to deal with the load and DG stochastic behaviours. In [185], the wind power and load demand uncertainties are considered by assuming they can be forecast in a time-frame optimisation, while in [163] these are modelled using PEM. However, the inaccuracies of these forecasts are neglected in that literature. The uncertainties of a hybrid system (solar PV and wind) and load demand are addressed in [116] by considering different scenarios of PV, wind, and loads. A special method (K-means method) is used for data clustering, thereby reducing the number of stochastic input scenarios. Similarly, the RES and load uncertainties are also taken into account in several studies [119,120,159,160,156,162,154,167] and modelled using different techniques. Though the above studies deal with uncertainties of RES generation and/or loads, the optimisation problem formulation for addressing these types of uncertainties is vitally important for future research of optimal ESS placement and operation.

The control of ESSs using different algorithms or approaches is very important for optimal ESS operation. Some control approaches are employed in [190,189,193,120,192,191]. In [193,191], ESS operations are facilitated through the coordination-based control method to provide voltage and frequency support. In [120], model predictive control (MPC) is applied to ESS operations for the power tracking and shaving of the distribution network. A stochastic stability enhancement strategy is employed in [189] for stable ESS operations. Furthermore, in [190], the real-time control of an active distribution network is accomplished through a multi-agent-system (MAS)-based decentralised control of ESSs. Besides these ESS control techniques, as discussed above and in Table 4, more control strategies can be employed to facilitate the optimal ESS operations in distribution networks.

Some studies introduce the mobile ESS concept which is also interesting from the ESS application viewpoint [126,194]. In [126], some important distribution network objectives – such as profit maximisation for the network operator, cost minimisation for imported grid power and voltage support – are achieved through mobile ESS scheduling and operation. Again, in [194], distribution system reliability is improved with mobile ESS deployment and operation. The optimal placement, scheduling, operation, and control of mobile ESSs can be investigated by applying different techniques in distribution networks.

Various types of performance and reliability indices for distribution networks are investigated in Table 4. In [164], distribution network reliability through ESS integration is investigated by addressing the indices momentary average interruption frequency index (MAIFI) and system average interruption duration index (SAIDI), while skipping other indices such as system average interruption frequency index (SAIFI), customer average interruption duration index (CAIDI), customer total average interruption duration index (CTAIDI), customer average interruption frequency index (CAIFI), average service availability index (ASAI), average system interruption frequency index (ASIFI), average system interruption duration index (ASIDI), customers experiencing multiple interruptions index (CEMIn), and customers experiencing long interruption durations index (CELID) [195]. On the other hand, in [162], network reliability is improved through optimal probabilistic-based ESS allocation, where the reliability indices are not considered. However, all of the reliability indices, including SAIDI, SAIFI, CAIDI, CTAIDI, CAIFI, MAIFI, ASIFI, ASAI, ASIDI, CEMIn, and

CELID are important for overall reliability analysis of distribution networks using ESSs and should be considered. The steady state characteristics of distribution networks are optimised in almost all relevant studies listed in Table 4, but transient or dynamic issues are neglected for optimal ESS placement and operation problems except [189] where the transient stability of ESS grid-tied inverter is only focused.

The charging impacts of electric vehicles (EVs) on distribution networks are also crucial. EV is a promising technology for the reduction of GHG emissions and the alleviation of climate change and global warming concerns [196–200]. With the targets for carbon emission reductions, governments of many countries are adopting EVs rather than conventional vehicles [196,198,200]. Furthermore, the potential contributions of EVs can facilitate continually increasing generation from intermittent RESs, e.g. wind [199,200]. Consequently, EVs are becoming more popular as sustainable transportation systems and are undergoing rapid development [196,198]. The increasing charging pattern of EVs has a considerable impact on distribution networks [196–198,201], including impacts on load profile, voltage profile, system components, power losses, phase unbalance, grid reliability, and harmonics, as well as power quality. Hence, optimal ESS placement and operation should consider the charging impact of EVs on a distribution network. In [167], EV charging stations and EV uncertainty are considered in optimal ESS planning in an active distribution network. The PEM is utilised in [162], another research on optimal ESS planning in distribution networks, to address the uncertainty of EVs. However, more research should be carried out in relation to optimal ESS placement and operation by considering various EV integration impacts, EV uncertainty, EV charging and discharging, and other optimisation parameters.

The optimal placement and operation of ESSs are very important for maximising network benefits. To obtain solutions for the optimal ESS placement and operation problems, various factors related to network performance and reliability should be considered. Identifying the optimal solution for ESS placement in a power system directly depends on the case studies (including system size and topology). This concept is evident in [114], where the optimum locations of ESSs are determined through simulation for two case studies, a low voltage (LV) distribution network in Western Australia and a medium voltage (MV) IEEE 33 bus system. Depending on the system size, the required number of ESSs to be installed in a network can be determined, which may satisfy the objective function of the problem. Take for example a micro-grid, which is a small section of a power system or distribution network. One ESS may be enough to mitigate system demand or power quality problems. However, for a large power system such as a distribution network, several ESSs may be required. In addition, the ESSs should be distributed in the network rather than centralised to provide more opportunities for problem mitigation and greater flexibility. For instance, analysing and comparing the applicability of distributed ESSs with a centralised ESS through simulation in [174] reveal that the distributed ESSs are more efficient. Again, the idea is validated in two case studies of [170] where the capacities of 42.3 MW and 29.2 MW are met by optimal placement of four and three ESSs respectively (with different capacities) at different buses. Although much research has been undertaken on these issues, comprehensive ESS models covering placement, operation, and sizing in a distribution network are needed for different case studies and scenarios.

As the mitigation of power quality problems is linked with optimal ESS placement, the next section discusses the ability of ESSs to mitigate various power quality problems and the importance of optimal ESS placement in distribution networks.

#### 3.4. Power quality problems and the role of ESSs

Power quality refers to the measurement, analysis, and improvement of the bus voltage for maintaining a sinusoidal waveform at rated voltage and frequency, which is generally meant to express the quality

**Table 5**  
Most common power quality problems [202–207,4,208,209,5,210–216,16,217,218].

| Issues                             | Definition  | Causes  | Consequences   | ESS role? |
|------------------------------------|---|---|--|-----------|
| 1. Voltage dip (or sag)            | When $V_{rms} < V_{nom}$ by 10–90% for 0.5 cycle to 1 min                               | Remote system faults, customer's installation faults, heavy load switching, large motor start-ups, and poor system maintenance and protection                     | Malfunction to microprocessor-based control systems, disconnection in electric rotating machines, loss of efficiency and lifetime, and tripping of electromagnetic relays          | Yes       |
| 2. Voltage swell                   | When $V_{rms} > V_{nom}$ by 10–80% for 0.5 cycle to 1 min                               | Heavy load switching, poorly regulated transformers, poor system maintenance and protection, and badly designed power sources                                     | Flickering of lights and screens, damage or stoppage of sensitive equipment, probable data loss, and electrical contact degradation  | Yes       |
| 3. Flicker or variable fluctuation | Repetitive fluctuations in $V_{rms}$ between 90% and 110% of $V_{nom}$                  | Frequent switching of large loads, arc furnaces, intermittent loads, RES integration, and welding plants  | Flickering of lights and screens, disturbing concentration, and creating headaches for people affected   | Yes       |
| 4. Voltage spikes/surges           | Abrupt alterations of voltage value for several $\mu s$ to few ms                       | Switching of lines or p.f. correcting capacitors, lightning, and disconnecting heavy loads  | Electromagnetic interference, data loss or processing errors, and damage to insulation materials and electronic components   | Yes       |
| 5. Overvoltage                     | When $V_{nom}$ rises above 110% for $> 1$ min   | Load variations, inappropriate tap setting and p.f. correction, motor starting, and decrease in demand  | Overheating, infrared process blistering, equipment damage, and reduce lifetime for lighting and electrical equipment  | Yes       |
| 6. Undervoltage                    | When $V_{nom}$ drops below 90% for $> 1$ min  | Poor wiring, unbalanced phase loading, incorrect tap setting, load variations, motor starting, reclosing activity with protection devices, and increase in demand | Instigates thermal effect and increase system loss, hardware damage, dimming and turning-on problems of some lights, creates errors, and reduces equipment efficiency and lifetime | Yes       |
| 7. Very short interruptions        | When electrical supply interruptions occur for few ms to 1 s or 2 s duration            | Opening and automatic reclosure of protection devices for clearing faults (due to lightning, insulator flashover, and insulation failure)                         | Malfunction to data-processing equipment and information loss, sensitive equipment stoppage, and unexpected tripping of protection devices   | Yes       |
| 8. Long interruptions              | When electrical supply interruptions occur for $> 1$ s or 2 s duration                  | Network equipment failure, acts of nature and accidents, failure or poor coordination of protection devices, fire and human errors                                | Equipment failure or shutdown, production losses, memory loss of computer or controller, and hardware damage   | Yes       |
| 9. Impulsive transients            | Large increase in V or I for a very short duration (1 ns – 1 ms)                        | Lightning strikes, electro-static discharge, intermixing of medium voltage and low voltage conductors, load switching, and fault clearing                         | Data loss, hardware damage for electronic equipment, and current limiting fuse operation   | –         |
| 10. Oscillatory transients         | Occurs when V or I rapidly changes polarity (+ve to -ve)                                | Switching of line, capacitor and load, resonant circuits, and poor device communications and wiring   | Data loss, electronic interference, and microprocessor-based equipment errors  | Yes       |
| 11. Voltage unbalance              | When voltage magnitudes or phase angles of a 3- $\phi$ system are not equal             | Unbalanced network impedances, unbalanced loads, large 1- $\phi$ loads (e.g., induction furnaces, traction loads) and their incorrect distribution                | Existence of -ve sequence and detrimental to 3- $\phi$ loads (unwanted heating, loss of efficiency etc.), maloperation of variable speed drive protection schemes and motors       | –         |
| 12. Harmonic distortion            | V or I waveform frequencies are multiple of fundamental (i.e. non-sinusoidal waveforms) | System resonance, non-linear loads, and use of equipment generating non-sinusoidal currents   | Overheating of equipment and cables, loss of efficiency in equipment, electromagnetic interference, errors in data measurement, and unexpected tripping of thermal protections     | Yes       |
| 13. Noise                          | When high frequency signals are superimposed on fundamental frequency                   | Improper grounding, electromagnetic interference by Hertzian waves, radiation from welding machines, electronic equipment, and arc furnaces                       | Data processing errors, probability of data loss, and disruption to sensitive electronic equipment   | –         |
| 14. Frequency deviation            | A deviation in fundamental frequency  | Large load fluctuations, start-up and shut down of large equipment, RES integration, and unstable frequency in power sources                                      | Data loss, system crashes, unexpected faults, disconnection to a large block of loads, damage to equipment, and large sources of generation forced off-line                        | Yes       |

$V_{rms}$  = RMS voltage,  $V_{nom}$  = Nominal voltage,  $\mu s$  = Micro-seconds, ns = Nano-seconds, V = Voltage, I = Current, p.f. = Power factor,  $\phi$  = phase.



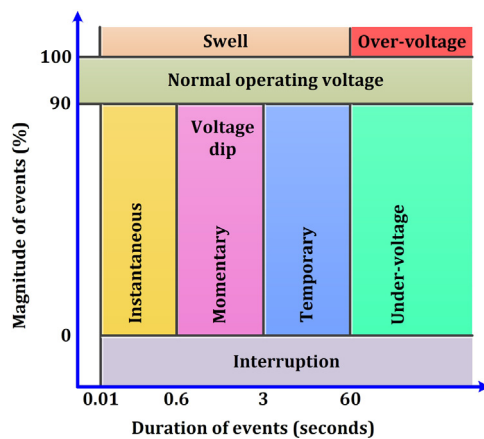


Fig. 4. Common voltage quality problems according to the IEEE Std. 1159–1995 [217].

of voltage and/or current [202]. The power quality of distribution networks may be affected by various issues as listed in Table 5 [202–207,4,208,209,5,210–216,16,217,218], which can affect the performance of sensitive loads and equipment. The steadiness of power demand, particularly for large companies or bulk tariff consumers and highly automated industries, can be affected by a network's power quality degradation. Therefore, power quality improvement in a distribution network is an important issue from the customer viewpoint [219].

Fig. 4 represents the most common voltage quality problems according to the IEEE 1159–1995 standard [218] for two durations: short ( $< 1$  min) and long ( $> 1$  min); where r.m.s variations (for short durations) are divided into three time intervals- instantaneous, momentary, and temporary. Depending on the disturbance voltage magnitude and duration, voltage quality issues such as voltage dip (or sag), voltage swell, interruption, overvoltage, and undervoltage can be demarcated [217,220]. The voltage profile management of large distribution networks is difficult because of the fluctuating behaviour of integrated RESs [221] and load demands [222], but it is crucial for power quality improvement. These oscillations can initiate steady state high/low voltage problems as well as voltage flickers, depending on the rate of change of voltage and various loading scenarios [223].

The exigency for ESS use to mitigate the impact of various power quality issues is highlighted in Table 2, which shows its potential for ameliorating most of the power quality problems in distribution networks. These include voltage dip, voltage swell, flicker, spikes or surges in voltage, overvoltage, undervoltage, short and long interruption, oscillatory transients, harmonic distortion, and deviation in frequency. For power quality improvement, ESS can be appropriate for fast, immediate, and high power responses which last for up to a few seconds [67], and for flicker compensation and voltage sag correction problems. For instance, they are useful for maintaining the network voltage within an endurable limit [224], which is obligatory for precise reactive power flow control and thus for generating high quality power [14]. In many cases, ESSs are introduced to solve power quality problems. As discussed in [221,225], power quality support can be provided by implementing ESSs at the point of common coupling through converters with the exchange of active and reactive power. An ESS, as a source of power connected to a dc-link, can also be coupled to FACTS (flexible AC transmission system) or DSTATCOM (distribution static synchronous compensator) [226] devices compensate for the system's active and/or reactive power unbalance. A new method is proposed for applying DSTATCOM with ESS to solve the flicker problem [225]. Again, ESSs are employed to offset the reactive power in [227], where the key drive is to eliminate harmonic distortions.

ESSs are used to minimise the overvoltage problem along with the

function of storing excessive energy in [228–230]. Using rooftop PVs, both overvoltage and undervoltage issues are addressed in [231] and a reactive capability of a PV inverter with ESS (battery) is proposed to ensure an acceptable voltage profile. Voltage fluctuations with the penetration of PVs are addressed and mitigated by introducing customer-side ESSs in [232–234]. An advanced voltage regulation method is proposed in [235] for distribution networks. This comprises dispersed ESSs and generation systems and considers an imbalance in the load diversity among feeders. However, improved voltage stability and more precise voltage regulation are still demanding issues. The authors in [80] propose using distributed ESSs to solve the voltage rise/drop problems in distribution networks (low voltage) with high penetration of rooftop PVs. The authors propose a coordinated control method to estimate the power outputs of ESSs in this research, which includes both distributed and localised SoC controls for distributed ESSs. The impact of an ESS (VRB), integrated with a PV source, on feeder voltages is investigated in a detailed simulation; however, the scenario may be challenged by the penetration of multiple RESs (e.g., PV and wind) in distribution networks.

The voltage profile can also be improved by controlling the reactive power. In [236], a droop control strategy for an ESS (ZnBr) combined with PV inverters is proposed for reactive compensation and hence for voltage profile improvement. However, the coordination of distributed ESSs in this research is challenging as the proposed control methods are applied in a decentralised structure. The power curtailment of PV or reactive power compensation is inexorable if the SoC of the ESS at a specific bus reaches defined limits. Quite the opposite is considered in [237]: a coordinated control of ESSs (distributed) with conventional voltage regulators is proposed to mitigate the voltage rise problem where the charging/discharging coordination of distributed SoC controllers is managed by a centralised controller.

A key review paper highlights how ESSs can also be beneficial for frequency control [14]. During transients, ESSs can play a major role in maintaining frequency stability by adjusting the grid frequency dynamically and hence improving the stability of the system [14]. The regulation of grid frequency is investigated with a new SoC feedback control strategy in [238], for a system comprising high penetration of wind generation and ESS. Another frequency control approach entirely reliant on ESS (batteries) is discussed in [239] to facilitate frequency regulation of an islanded power system (with no RESs). Likewise, in [240], a peerless control algorithm with flexible SoC limits of an ESS (battery as spinning reserve application) is employed for frequency control of an isolated power system.

The potential of ESSs to mitigate power quality problems and sustain healthy networks has been validated in the above literature. However, the most important goal is to extract the maximum benefit from using ESSs for power quality improvement via the optimal placement of ESSs in a distribution network. There is little research on solving power quality issues with optimal ESS placement. A number of optimisation problems, such as voltage flicker, overvoltage, and undervoltage, should be addressed to realistically solve power quality problems via optimal ESS placement. For example, if the ESS location is selected arbitrarily in a network where the voltage flicker or dip problem does not generally exist, then the ESS placement will not mitigate network power quality problems, which may happen for other power quality issues set out in Table 5.

#### 4. Implementation and performance

The relevant literature for optimal ESS placement, sizing, and operation, and related power quality issues has been reviewed in the preceding section. Below, development and implementation challenges, optimisation approaches to obtain ideal distribution network performance, the social impact of ESS placement, and related energy security issues are discussed.

#### 4.1. Development and implementation challenges

For optimal ESS placement, development and implementation challenges must be considered. Development issues include appropriate planning and modelling, realistic data analysis, determination of optimisation factors (such as power quality problems, cost, stability, and reliability issues), suitable ESS selection and sizing should be addressed thoroughly, while initial investment, ESS deployment barriers, and performance analysis after placement are important implementation issues.

Appropriate planning and system modelling are essential first development steps for optimal ESS placement in a distribution network. Following this, a thorough analysis of realistic data for that network should be undertaken to identify various network problems. Subsequently, the important factors for optimisation should be determined for a location or multiple locations in that network. Finally, the appropriate selection of ESSs and their sizes can be completed in order to target the problems, optimisation factors, and network benefits.

A key implementation challenge is the substantial initial investment for ESSs. Additional deployment barriers include:

- (a) Utility processes and regulations not favouring the ESSs;
- (b) Insufficient awareness of ESS benefits among stakeholders [241].

Another important issue is the lack of large-scale production to meet required power and energy capabilities, especially for distribution network levels [241]. These problems can be solved through enlisting government funding support, streamlined supervisory approvals, and offers of tax incentives to encourage investors to focus on specific ESS technology [241]. After deploying ESSs in a distribution network, performance analysis is also important.

#### 4.2. Optimisation approaches in achieving optimum performance

##### 4.2.1. Various optimisation approaches

Choosing the optimal places and sizes of ESSs in a distribution network is not straightforward. To maximise distribution network performance, the appropriate selection of optimisation approaches is another key benchmark. There are various categories of optimisation methods, such as classical, analytical, and meta-heuristic [242–244]. Although these types of optimisation approaches are suitable for some applications, they also have disadvantages. The OPF, a classical approach, is suitable for highly complex problems, but has limitations for power systems with high dimensionality [245]. Similarly, although linear programming is easy to implement [199], it is generally difficult to represent models as a set of linear equations [246]. Analytical approaches are suitable for small and simplistic systems with few state variables and provide very accurate results relatively quickly. Nevertheless, their selection is not appropriate for large and complex system, especially in less straightforward applications, with size complications and the varied characteristics of distribution networks. They may also generate imprecise solutions for real time problems [243]. Some examples of this category are the PEM, eigen-value-based analysis (EVA), index method (IM) and sensitivity-based method (SBM). Meta-heuristic approaches are most appropriate for solving challenging problems in distribution networks (many of these are inspired by nature) and are capable of providing accurate, efficient, and optimal solutions. However, meta-heuristic techniques also have some limitations since they do not always offer the optimal solution, and in most real-life problems, some assumptions cannot be satisfied. Algorithms in this category include GA, PSO, artificial bee colony (ABC), ant colony optimisation (ACO), harmony search, and chaotic algorithms.

Meta-heuristic techniques are considered in several studies for optimising the placement, sizing, and operation of ESSs in power networks. A GA is used in [247] to place and size a single ESS in order to achieve network benefits in relation to the reduction of voltage

deviation, losses, and costs. GAs are also applied in [248] to determine control strategies, e.g., controlled gain factors for hybrid power generation and in [249] for ESS sizing and operation to help defer investment, manage electricity price arbitrage, and reduce access costs for transmission. Furthermore, GA is employed in [171] for optimal ESS allocation and operation when facilitating large-scale wind power integration. Again, GA is used to place an ESS (SMES) in [250] to maximise the voltage stability index. Another meta-heuristic approach, PSO, is used in [175] for optimum allocation of standby ESSs to minimise distribution network costs. In [149], the PSO is applied to ESS sizing and the minimisation of the total levelised cost, while achieving cost benefits for an ESS used in a grid-connected, stand-alone PV system for both short- and mid-term periods. In [173], a fuzzy PSO, associated with a cost benefit analysis, is employed for optimal allocation of ESSs to mitigate risk for distribution companies (DISCOs). In [148], the advanced artificial neural network (ANN) is utilised for optimal ESS sizing in a large-scale wind farm while increasing output predictability and reducing wind integration cost. The results are compared with other approaches, e.g., general, fuzzy, and simple ANN. A tabu search (TS) algorithm is used in [251] for ESS sizing by taking into account unit commitment. The multi-objective strength pareto evolutionary algorithm 2 (SPEA2) [252] is utilised in [253] to place multiple ESSs in a distribution network intended to providing arbitrage and ancillary services as well as voltage support. Simulated annealing (SA) is applied to ESS allocation in [254] to offer an emergency backup service for power networks: it allows non-improving moves to be detected for escaping local optima [255].

Although meta-heuristics having some advantages, they do not have strong global and local search abilities and hence do not always guarantee a globally optimal solution compared to classical approaches such as linear programming. For instance, the ABC algorithm, which is recognised as a relatively new bio-inspired swarm intelligence approach, is competitive with other population-based algorithms [256,257] but can be trapped in local optima when global optimisation is sought, as reported in [258]. Research continues with the intention of improving the existing approaches and hybridising meta-heuristic approaches with other approaches or their modifications to offer more effective solutions [243,259].

##### 4.2.2. Hybrid meta-heuristic approaches

The hybridisation of a meta-heuristic with other optimisation algorithms, known as the hybrid meta-heuristic approach, may achieve globally optimal solutions and provide optimum solutions to distribution network problems according to [243] which presents a detailed picture of all methods in different categories and concludes in favour of hybrid meta-heuristic approaches. The hybrid meta-heuristic techniques combine two or more algorithms having different strengths and offer the best solution by eliminating limitations of a single meta-heuristic approach. These techniques can be robust and powerful tools for global optimisation, can tackle various multi-objective (constrained and unconstrained) problems, and obtain high-quality results with relatively few function evaluations [243]. For instance, the ABC has poor local search ability but strong global search capability [260], while the reverse is true for PSO [261]. The ABC algorithm is combined with PSO in [262] to eliminate shortcomings and provide a well-balanced hybrid with powerful local and global searching abilities. To evade the major shortcomings of the classical simple GA, a new hybrid algorithm combining GA and TS is proposed in [263]. In another example, ACO and ABC are amalgamated to blend their continuous and discrete optimisation features and develop a new hybrid ACO-ABC-based optimisation algorithm [264]. Similarly, the ABC algorithm is merged with the harmony search in [265] and the chaotic algorithm in [266] to overcome its major limitation and achieve a best global optimisation approach along with a strong local search ability.

The PSO is hybridised by integrating non-dominated sorting genetic algorithm II (NSGA-II) in [170] for ESS placement and sizing in a

distribution network that addresses wind power uncertainty. To obtain an optimal solution for the ESS placement, sizing, and operation problems and minimise the complexity of objective functions, the GA is combined with linear programming in [115,172], and with a sequential quadratic programming technique to place capacitors and ESS in [146]. The GA is combined with a market-based probabilistic OPF in [174] for the optimal placement of ESSs in a deregulated power system with high wind penetration.

Thus, hybrid meta-heuristic approaches can be applied as robust methods for the optimisation of complex, nonlinear objective functions which not only enhance the potential for exploitation and convergence but also provide better results [243]. As these techniques offer optimum solutions with a reduced number of iterations, they can be used to deal with distribution network problems with regard to ESS placement, sizing, and operation and can facilitate the optimum performance of distribution networks.

#### 4.3. Social impact and energy security

It is crucial to be aware of the distribution grid situation, deal with real-time grid problems and yield optimum solutions. Since the optimal placement, sizing, and operation of ESSs can mitigate the related grid problems of power quality and the sudden increase or decrease in load demand, these strategies can contribute to the optimum performance of the distribution network and ensure a quality power supply to consumers. Moreover, the optimal placement of ESSs assists in avoiding distribution network expansion costs as demand rises. Furthermore, the optimal control or operation of ESSs allows the operators of electrical distribution systems to improve reactive control and reduce overall costs.

Due to the lack of new generation capacity and the risk of fuel costs increasing, deregulated electricity markets are developing in most advanced countries to promote competition in electricity supply markets. The restructuring of these markets has led to distinct generation, transmission, distribution, and retailing processes. One of the outcomes of market-place reform is the emergence of third-party entities known as retailers who procure electricity from various electricity sources (e.g., the electricity pool, spot markets, and self-production units), and resell it as the sole provider to customers [267,268]. Retailers need to make effective decisions about sources and the amount of electricity they procure, as these electricity sources have different variable characteristics over time [269,270]. Retailers generally try to manage the risk involved in purchasing electricity from those sources by offering fixed or variable electricity prices to their consumers. However, load uncertainty still creates risks, which can be accommodated by the flexible operation of ESSs and implementing smart scheduling strategies while optimising the cost of energy purchased [115,172,185]. In this context, optimally placed ESSs may be an effective way for retailers to manage variable loads and reduce risks while optimising their profits and consumer satisfaction.

More importantly, the optimal placement of ESSs will encourage operators to add more RES generation (e.g., solar and wind) to the grid supply. For instance, the world's largest ESS (Li-ion) of 100 MW capacity is installed by Tesla in South Australia. The ESS is integrated with a wind farm and capable of powering 30,000 homes for up to an hour in the event of a blackout [271]. Thus, the placement of such ESSs makes the grid supply more environmentally sustainable and reliable without hampering other non-renewable generation and profit making opportunities for the operators. As achieving energy security is a high priority for a society, optimal ESS placement, sizing, and operation can provide safe and secure energy management.

## 5. Conclusions

This paper has provided a comprehensive overview of the issues relating to the use of ESSs in electricity networks. It has presented some

key ideas for the optimal choice of ESSs, the smart charging and discharging of ESSs, ESS placement, sizing, and operation, and the mitigation possibilities of power quality issues by ESS placement. Furthermore, for optimal ESS placement, this paper has identified development and implementation challenges, and has discussed the suitability of hybrid meta-heuristic optimisation approaches, and has also considered social impact. Some recommendations are provided at the end of this section. However, more research is needed on the impacts of ESS placement in a distribution network in relation to optimum demand management, power quality management, the cost of the distribution network, power loss reduction, RES or DG integration, and grid stability and reliability. Through understanding ESS placement issues and possible impacts after placement, the deployment of ESSs in a distribution network and the associated development of smart grids will be greatly facilitated.

Overall, ESSs can improve the performance of a distribution network. The objectives for attaining desirable enhancements such as energy savings, distribution cost reduction, optimal demand management, and power quality management or improvement in a distribution network through the implementation of ESSs can be facilitated by optimal ESS placement, sizing, and operation in a distribution network. Optimal ESS placement, along with sizing and operation, are highly important for greater RES integration in the distribution network and thus for reduced carbon emissions. After reviewing the available research work on ESS placement, sizing, and operation issues, the following recommendations are made for future research to address the identified gaps:

- Although there are various types of ESSs with extensive advantages and disadvantages, the optimal choice of ESS will depend on the expected performance enhancements, ESS characteristics, and application types. While batteries are widely used ESSs in various applications, the detailed comparative analysis of ESS technical characteristics conducted in this paper suggest that FES also warrants more consideration, in terms of benefits, in some distribution network scenarios.
- The smart charging and discharging of ESSs are both crucial for saving energy, achieving optimum ESS efficiency, increasing ESS lifetime and achieving cost-effective network operation. Further research on the application of smart charging and discharging algorithms for optimal ESS implementation is recommended.
- Optimal ESS sizing should be accomplished by considering all costs directly related to the benefits of selected case studies. Furthermore, a comparison of the selected ESS (after sizing) with other possible types in regard to cost and performance is recommended to explore an appropriate ESS option for a specific location in a distribution network.
- If RESs are integrated in the distribution grid, the uncertainties associated with renewables should be addressed when optimising ESS placement. Moreover, due to the intermittency of many RESs, the consideration of power quality issues in problem formulation is highly recommended.
- For demand-side management and appropriate system modelling with fluctuating loads and EVs, load and EV uncertainties must be considered in the optimal ESS placement problem. The EV charging impacts to distribution networks should also be incorporated during system modelling and objective function formulation. Moreover, various ESS control approaches (e.g., MAS) can be employed to facilitate optimal ESS operation in distribution networks.
- The optimal solution of ESS placement problems directly relies on case studies, especially in regard to network topology and system size. The number of required ESSs in an LV distribution network may be lower than in an MV network, and the distributed structure of ESS placement with more than one ESS is highly recommended to allow better system performance and flexibility in mitigating problems.



- As global warming and pollution are pressing issues, environmental and geographical constraints must be considered along with technical and economic constraints to provide a realistic solution for optimal ESS placement. For instance, the installation of ESSs should not be allowed in certain buses of distribution networks due to right of way issues. Some environmental and geographical constraints are neglected during problem formulation in a large portion of the literature (see the research summarised in Table 4).
- Although many strategies have been applied for tackling optimal ESS placement, sizing, and operation problems, more research effort should be applied to optimising transient/dynamic issues rather than the steady state characteristics of a distribution network. The reliability of a distribution network with ESSs should be analysed through the verification of reliability indices such as SAIDI, SAIFI, CAIDI, CTAIDI, CAIFI, MAIFI, ASIFI, ASAI, ASIDI, CEMIn, and CELID.
- Some major power quality problems can be mitigated by optimal ESS placement and operation as indicated in Table 5. Therefore, issues such as voltage flicker and overvoltage or undervoltage should be specified for a particular network place and included in the optimisation problem.
- Although several meta-heuristic approaches for optimisation have already been established by researchers, improvement is still required. The hybridisation of a meta-heuristic with other optimisation algorithms (namely hybrid meta-heuristic), with proper setting of control parameters, or developing more efficient meta-heuristic approaches for global optimum search is recommended.

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